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THESIS

DECISION ANALYSIS TO SUPPORT CONDITION-BASED MAINTENANCE PLUS

by

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June 2006

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DECISION ANALYSIS TO SUPPORT CONDITION-BASED MAINTENANCE PLUS

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ABSTRACT

This thesis provides a stochastic modeling tool to assist in the component selection process for Army Aviation's Condition-Based Maintenance Plus (CBM+) program. The CBM+ program uses measurements from sensors to monitor the health (resistance to failure) of components replacing the Legacy process of scheduled inspections and maintenance. This work is in conjunction with the Operations Research Center of Excellence (ORCEN) at the United States Military Academy to assist in providing insight for the U.S. Aviation and Missile Command (AMCOM). AMCOM is currently developing CBM+ from its current early stages into a program that will revolutionize maintenance procedures for the Army's helicopter fleet.

The subsystem selected for this thesis is the AH-64/UH-60 T701C Turbine Helicopter Engine. The times to occurrences to serious diagnostics symptoms requiring maintenance action were collected from the Army's Aviation and Missile Research, Development, and Engineering Center (AMRDEC). Data analysis indicates that a nonhomogeneous Poisson process appropriately models the times between the occurrences of serious diagnostic symptoms for this engine. A Microsoft Excel simulation utilizing Crystal Ball version 5.5 compares an engine monitored by CBM+ versus the traditional Legacy system of maintenance. This simulation provides information on diagnosed faults, mission aborts, repair times, false positives, and logistical implications.

This simulation is generic and can be used in comparing CBM+ candidate components for future inclusion into the CBM+ program. Results suggest that the sensor's false alarm rate and the reliability/maintainability of the CBM+ sensor are important factors to consider. Since the CBM+ sensor is continually monitoring a component's condition, a modest sensor probability of detection of an impending failure can result in fewer mission aborts than those that arise in the Legacy system. The ability and speed of the logistics system to recognize and respond to sensor measurements indicating impending failure affect the potential success of CBM+.

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EXECUTIVE SUMMARY

U.S. Aviation and Missile Command (AMCOM) has initiated a program to monitor Army helicopter component health (resistance to failure) through a network of sensors installed on aircraft. This sensor network forms the foundation for a maintenance philosophy known as Condition-Based Maintenance Plus (CBM+). This thesis provides a stochastic modeling tool to assist in the component selection process for Army Aviation's CBM+ program. This work is in conjunction with the Operations Research Center of Excellence (ORCEN) at the United States Military Academy to assist in providing insight for the U.S. Aviation and Missile Command (AMCOM). AMCOM is currently developing CBM+ from its current early stages into a program that will revolutionize maintenance procedures for the Army's helicopter fleet. The CBM+ program uses measurements from sensors to monitor the health of components replacing the Legacy process of scheduled inspections and maintenance. Furthermore, Army Aviation's CBM+ program is a collection of maintenance processes and capabilities derived, in large part, from real-time assessment of weapon system condition, obtained from embedded sensors and/or external tests and measurements. Currently, aircraft parts are replaced based on results of scheduled maintenance inspections of the Legacy maintenance system. Under CBM+, the condition of components will be monitored and the components replaced when sensors show indications of possible failure and extended wear.

Not all components will benefit from being part of the CBM+ program. Stochastic modeling and simulation are used to develop a tool to assist in the component selection process for CBM+ program. This work is in cooperation with the Operations Research Center of Excellence (ORCEN) at the United States Military Academy supporting AMCOM.

The subsystem selected for this thesis is the AH-64/UH-60 T701C Turbine Helicopter Engine. The times of occurrences of serious diagnostics symptoms requiring maintenance action were collected from the Army's Aviation and Missile Research, Development, and Engineering Center (AMRDEC) and analyzed to provide input to the

development of a simulation model. The resulting Microsoft Excel simulation utilizing Crystal Ball version 5.5 compares an engine monitored by CBM+ versus the traditional Legacy system of maintenance. The output of the simulation provides information on diagnosed faults, mission aborts, repair times, false positives, and logistical implications.

This simulation is generic and can be used in comparing CBM+ candidate components for future inclusion into the CBM+ program. Results from the simulation study suggest that since a sensor is continually monitoring the component, it doesn't have to be highly accurate in diagnosing impending failures in order to produce fewer mission aborts than the Legacy maintenance system. However, it is extremely important to minimize the number of false positives when using CBM+ sensor otherwise the Legacy maintenance system outperforms CBM+ with respect to total inspection/repair time.

I. INTRODUCTION

A. CONDITION-BASED MAINTENANCE PLUS

U.S. Aviation and Missile Command (AMCOM) is interested in monitoring Army helicopter component health through a system of sensors and monitors placed onboard aircraft. Component health is defined as a component's ability to provide the proper mechanical action it was designed and engineered to accomplish. This program is in response to a Department of Defense (DoD) strategy which states that all services should seek "operational supportability" in system development and demonstration. (DoD 5000.2, 2003) Over the past year, approximately twenty different aircraft components were monitored by sensors; the components are installed on different types of airframes. The AH-64 Apache, UH-60 Blackhawk, and CH-47 Chinook were selected since these are the aircraft that are included in the Army's force modernization plan. This sensor network forms the foundation for a maintenance philosophy known as Condition-Based Maintenance (CBM).

According to Defense Acquisition Guidebook dated 20 December 2004 "the goal of CBM is to perform maintenance only upon evidence of need. CBM tenets include: designing systems that require minimum maintenance; need-driven maintenance; appropriate use of embedded diagnostics and prognostics through the application of Reliability-Centered Maintenance (RCM); improved maintenance analytical and production technologies; automated maintenance information generation; trend based reliability and process improvements; integrated information systems providing logistics system response based on equipment maintenance condition; and smaller maintenance and logistics footprints." (Department of Defense, 2003) A more specific form of CBM exists and that is known as Condition-Based Maintenance Plus (CBM+). CBM+ "expands on these basic concepts, encompassing other technologies, processes, and procedures that enable improved maintenance and logistics practices. CBM+ can be defined as a set of maintenance processes and capabilities derived, in large part, from real-time assessment of weapon system condition, obtained from embedded sensors and/or external tests and measurements. The design specifications should identify early teaming with systems engineering to clearly define and understand the operating

envelope in order to design in Built-In-Test (BIT) and Built-In-Self-Test (BIST) mechanisms including false alarm mitigation.” (Department of Defense, 2006) False alarm mitigation is accomplished by using sensor equipment that provides for enhanced capability for fault detection, isolation, and repair time minimization. The purpose of this enterprise is to provide cost-effective warning of potential catastrophic failure or mission abort.

AMCOM’s mission statement is “to transform Army Aviation maintenance to Condition-Based Maintenance, by converting condition and usage data into maintenance actions.” (AMCOM Web Site, 2006) Currently, aircraft parts are replaced based on a system of scheduled maintenance inspections. CBM+ would drastically change this system. Under CBM+, components would now be monitored and replaced only when sensors show indications of ill health or possible imminent failure and extended wear. AMCOM contacted the Operations Research Center of Excellence (ORCEN) at the United States Military Academy to assist in providing additional insight into this important area of research. This thesis is produced in conjunction with ORCEN in an effort to provide AMCOM with a stochastic model and simulation that will be useful in aiding decisions concerning the potential introduction of aircraft components to CBM+.

Currently, only passive sensors are employed on Army aircraft. After each flight the crew chief downloads data from the sensors onto a recording device. The crew chief then transfers the data to a laptop computer for that specific aircraft. All of the crew chiefs’ laptop computers feed into a desktop computer at the unit’s Production Control office. The Production Control office is the controlling node for all maintenance activities of an Army Aviation unit. B.F. Goodrich contact teams are at specific sites and are assisting these Production Control offices with interpreting the data. Based on these interpretations these data can trigger repair or replacement of components. The data are then sent from the Production Control office to a data warehouse which is currently undergoing construction by the Westar Corporation. From this data warehouse AMCOM reviews the data and monitors the development of CBM+.

B. OBJECTIVES

The objective of this thesis is to utilize stochastic modeling and simulation to aid in determining which aircraft components should be included in CBM+. Microsoft Excel 2003 and Crystal Ball version 5.5 were chosen as the software package for the simulation of this model. (Ragsdale, 2004) Crystal Ball version 5.5 is an Excel-based Monte Carlo simulation application produced by Decisioneering Incorporated. The components that have been selected to use CBM+ were chosen as a test bed to make sure that the CBM process results in a decrease of the maintenance burden on the soldier, an increase in platform availability and readiness, and a reduction of operations and support costs. (Brown, 2005) Since AMCOM is in the earliest phases of CBM+, it acquired sensors to track and monitor aspects that its engineers hypothesized would have a useful probability of providing the most beneficial results in terms of improving operational readiness and reduction of maintenance related costs. Now that results have been generated there needs to be a component selection system established that will be used when CBM+ is implemented across the Army aviation fleet.

The simulation used in this thesis compares a CBM+ monitored airframe to a non-CBM+ monitored airframe. The measures of performance include mitigation of mission aborts, time spent repairing components, and time spent awaiting replacement component arrival. Through this comparison it is possible to determine which components to enter into the program based on the greatest reduction of mission aborts and possible gain in mission performance and operational readiness. This can be a useful tool for AMCOM to use in future decision making.

C. LEGACY AND CONDITION-BASED MAINTENANCE PLUS REGIMES

A Legacy unit that conducts maintenance using the conventional maintenance regime is currently in place at all Army aviation units. A CBM+ unit conducts the Legacy maintenance regime but also has the benefit of CBM+ sensors installed on specified components. Both regimes employ intensive scheduled maintenance and reactive unscheduled maintenance. The use of CBM+ monitoring promises to reduce numerous time-intensive scheduled maintenance actions, reduce the unexpected nature of

unscheduled maintenance, and increase operational readiness. (Department of the Army, 2004) An example of this is Air Worthiness Release (AWR) dated 16 June 2005, which deleted mandatory inspection requirements for six different CBM+ monitored components on AH-64 Apache and UH-60 Blackhawk helicopters. This AWR saved Maintenance Man Hours (MMH) per inspection, downtime per aircraft, and Time Between Overhaul (TBO) for components. This AWR is the first of many of its kind that will transition Army Aviation from the present rigid, time-intensive, and reactive Legacy maintenance regime to a prediction-based CBM+ maintenance regime.

D. METHODOLOGY

This thesis is divided into six chapters and follows this structure. Chapter I, “Introduction,” describes the background, objectives, and methodology of this work. Chapter II, “Aircraft System Structure and Data,” discusses in detail the aircraft components that are currently monitored by Condition-Based Maintenance Plus and the available data describing their performance, failure, and repair. This chapter describes the maintenance procedures used by Army aviation units and the repair times associated with these actions. Chapter III, “Stochastic Models for Comparing Legacy Maintenance and Condition-Based Maintenance Plus,” details the model structures, and gives example cases of the stochastic model that is used in this thesis. Chapter IV “Legacy Maintenance and Condition-Based Maintenance Plus Simulation,” describes the architecture, characteristics, assumptions, and results of the simulation used in this thesis. Chapter V, “Data Analysis,” presents the results of the analysis of the simulation output as different components are monitored and compares average operational readiness and repair times. Finally, Chapter VI, “Conclusions and Recommendations,” summarizes the findings of this thesis and possible uses for this thesis in future decision making.

II. AIRCRAFT SYSTEM STRUCTURE AND DATA

A. GENERAL DESCRIPTION OF AIRCRAFT TYPES AND COMPONENTS

This chapter will discuss in detail the aircraft components that are currently in the Condition-Based Maintenance Plus program or are under consideration for inclusion. Any available data describing their performance, failure, and repair are listed. Furthermore, this chapter describes the maintenance procedures used by Army aviation units and the costs associated with these actions; all CBM+ sensors currently use vibratory information to monitor these components. The three different types of aircraft presently monitored by CBM+ are the AH-64 Apache, UH-60 Blackhawk, and the CH-47 Chinook.

1. AH-64 Apache Helicopter Information

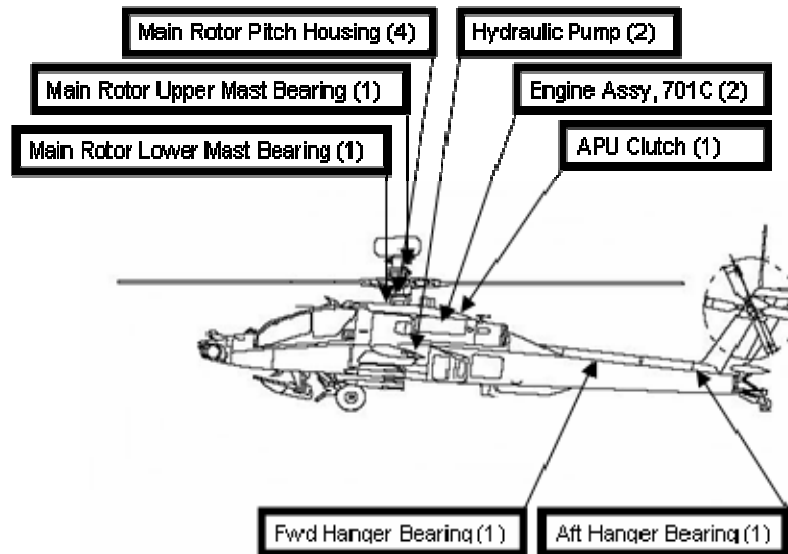
The AH-64 Apache helicopter is a twin-engine, tandem-seat, aerial weapons platform. (TM 1-1520-251-10, 2002) Its primary mission is to provide attack and reconnaissance capabilities in support of the ground tactical plan. There are currently thirteen components of eight different types monitored by CBM+ on the AH-64. A listing of AH-64 Apache CBM+ components is listed in Table 1.

Table 1. AH-64 Apache CBM+ Component Listing

| AH-64 COMPONENT NOMENCLATURE | NSN | PART NUMBER | FEDLOG NOMENCLATURE |
|------------------------------|------------------|----------------|-----------------------------|
| APU Clutch | 3010-01-515-8483 | 3617950-1 | CLUTCH ASSEMBLY,FRICTION |
| Engine Assembly, 701C | 2840-01-284-4011 | 6071T24G01 | ENGINE,AIRCRAFT,TURBO-SHAFT |
| Utility Hydraulic Pump | 4320-01-158-0893 | 7-311810022-3 | PUMP,AXIAL PISTONS |
| Forward Hanger Bearing | 3130-01-333-8491 | 7-311350008-5 | BEARING UNIT,BALL |
| Aft Hanger Bearing | 3130-01-333-8490 | 7-211350007-5 | BEARING UNIT,BALL |
| MR Pitch Housing | 1615-01-235-5845 | 7-311411215-13 | HOUSINGASSEMBLY |
| MR Upper Mast Bearing | 3110-01-215-4794 | 7-311411202-5 | BEARING,ROLLER,TAPERED |
| MR Lower Mast Bearing | 3110-01-179-7335 | 7-114110011 | BEARING,ROLLER,TAPERED |

Depicted below in Figure 1 is the location of these components on the AH-64 Apache extracted from Figure 2-2 of TM 1-1520-251-10. The number in parenthesis indicates the total number of that type of component on the aircraft.

Figure 1. Location of AH-64 Apache CBM+ Components



2. UH-60 Blackhawk Helicopter Information

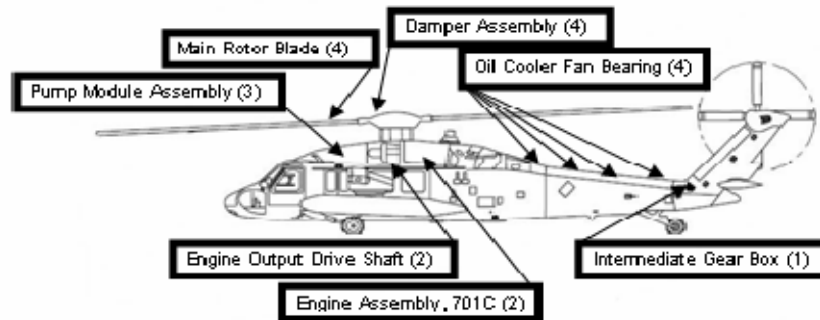
The UH-60 Blackhawk helicopter is a twin-turbine engine, single-rotor, semimonocoque fuselage helicopter. Its primary mission is the tactical transport of troops, supplies and equipment. Its secondary missions include training, mobilization, development of new and improved concepts, and support of disaster relief. (TM 1-1520-237-10, 2003) There are currently nineteen components of eight different types monitored by CBM+ on the UH-60. A listing of UH-60 Blackhawk CBM+ components is listed in Table 2.

Table 2. UH-60 Blackhawk CBM+ Component Listing

| UH-60 COMPONENT NOMENCLATURE | NSN | PART NUMBER | FEDLOG NOMENCLATURE |
|------------------------------|------------------|-----------------|----------------------------------|
| Oil Cooler Fan Bearing | 3110-01-329-8573 | 110KSZZ-401 | BEARING,BALL,ANNULAR |
| Main Rotor Blade | 1615-01-106-1903 | 70150-09100-043 | BLADE,MAIN ROTOR |
| Pump Module Assembly | 4320-01-207-7228 | 70652-02300-050 | MODULE ASSY,PUMP |
| Damper Assembly | 1615-01-285-3024 | 70106-08100-046 | DAMPENER,FLUTTER |
| Engine Assembly, 701C | 2840-01-284-4011 | 6071T24G01 | ENGINE,AIRCRAFT,TURBO-SHAFT |
| Engine Output Drive Shaft | 2835-01-123-7648 | 70361-08004-043 | DRIVE SHAFT ASSEMBLY,ROTARY WING |
| Intermediate Gear Box | 1615-01-074-5152 | 70357-06300-042 | GEAR BOX ASSEMBLY |

Depicted below in Figure 2 is the location of these components on the UH-60 extracted from Figure 2-2 of TM 1-1520-237-10. The number in parenthesis indicates the total number of that type of component on the aircraft.

Figure 2. Location of UH-60 Blackhawk CBM+ Components



3. CH-47 Chinook Helicopter Information

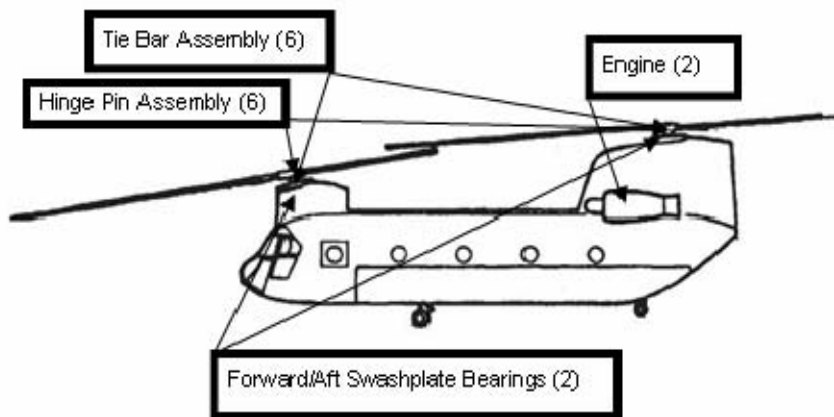
The CH-47 Chinook is a twin-turbine engine, tandem-rotor helicopter. Its primary mission is the transportation of cargo, troops, and weapons during day, night, visual, and instrument conditions. (TM 1-1520-240-10, 2003). There are currently sixteen different components of four different types on the CH-47 monitored by CBM+. A listing of CH-47 Chinook CBM+ components is listed in Table 3.

Table 3. CH-47 Chinook CBM+ Component Listing

| CH-47 COMPONENT NOMENCLATURE | NSN | PART NUMBER | FEDLOG NOMENCLATURE |
|------------------------------|--------------------------------------|--------------------------|-----------------------------|
| Hinge Pin Assembly | 5315-01-295-7008 | 114R2197-7 | PIN,HOLLOW |
| Tie Bar Assembly | 1615-00-740-6480 | 114R2155-1 | TIE BAR ASSEMBLY,LAMINATED |
| Engine, Gas Turbine | 2840-01-458-5361 | 2-001-020-39 | ENGINE,AIRCRAFT,TURBO-SHAFT |
| Fwd/Aft Swashplate Bearings | 3110-00-141-3750 3110-01-356-0489 | 114RS308-1 114RS308-2 | SWASHPLATE BEARING |

Depicted below in Figure 3 is the location of these components on the CH-47 extracted from Figure 2-1-1 of TM 1-1520-224-10. The number in parenthesis indicates the total number of that type of component on the aircraft.

Figure 3. Location of CH-47 Chinook CBM+ Components



B. SPECIFIC DESCRIPTION OF COMPONENT CHARACTERISTICS

Brief descriptions of the components of interest on the AH-64 Apache referenced from TM 1-1520-251-10 are:

1. Auxiliary Power Unit Clutch is a subcomponent of the Auxiliary Power Unit (APU) which provides both hydraulic pressure, pressurized air, and electrical power for

the operation of systems onboard the AH-64 whether the engines are operating or not. The APU is required to start the main engines unless the AH-64 is assisted with an Auxiliary Ground Power Unit (AGPU).

2. 701C Engine Assemblies are the main engines for the AH-64. The engines are front drive turbo shaft engines of modular construction. One horizontally mounted engine is housed on either side of the AH-64 aft of the main transmission above the wing.

3. Utility Hydraulic Pump is a subcomponent of the utility hydraulic system that provides hydraulic power to the flight controls, weapon drives, ammunition systems, and emergency hydraulic systems. This pump is mounted on the accessory drive case of the main transmission (right side).

4. Forward Hanger Bearing is a component of the tail rotor drive system. A hanger bearing supports the two longest shafts of three shafts that lead from the transmission to the intermediate gear box. There is a fourth shaft that leads from the intermediate gear box to the tail rotor. The forward hanger bearing is located on the end of the second shaft.

5. Aft Hanger Bearing serves the same purpose as the Forward Hanger Bearing; it is located on the end of the third shaft.

6. Main Rotor Pitch Housing is a subcomponent of the rotor head. The pitch housing permits blade pitch changes in response to flight control movements transmitted through the swashplate.

7. Main Rotor Upper Mast Bearing is a subcomponent of the AH-64 mast collocated with the rotor head.

8. Main Rotor Lower Mast Bearing is similar to the upper bearing but located lower.

Brief descriptions of the components of interest on the UH-60 Blackhawk referenced from TM 1-1520-237-10 are:

1. Oil Cooler Fan Bearing is a subcomponent of the tail rotor drive section. The oil cooler cools oil from the engine before it returns it to the oil tank. Shafts from the main transmission connect the oil cooler and also transmit torque to the tail rotor. There

are four points where viscous damped bearings are mounted on adjustable plates which support these shafts that lead to the tail rotor.

2. Main Rotor Blades are a subsystem of the main rotor system. A rotor blade has a titanium-spar and is attached to spindles which are retained by elastomeric bearings contained in one-piece titanium hub. The elastomeric bearing permits the blade to flap, lead, and lag.

3. Pump Module Assembly is a component that provides hydraulic pressure to the Blackhawk's hydraulic system. The hydraulic pump module assemblies are a combination of a hydraulic pump and a hydraulic fluid reservoir.

4. Damper Assembly is located between the main rotor blade and the main rotor head. Main rotor dampers are installed between each of the main rotor spindles modules and the hub to restrain leading and lagging motions of the main rotor blades during rotation and to absorb rotor head loads when starting the aircraft. Each damper has a small hydraulic fluid reservoir.

5. 701C Engine Assemblies are the main engines for the UH-60. The engines are front drive turbo shaft engines of modular construction. One horizontally mounted engine is housed on either side of the UH-60. These are the same engines that are mounted on the AH-64 Apache.

6. Engine Output Drive Shaft is a subcomponent of the UH-60 power train system. It transfers torque generated by the engine to the main transmission.

7. Intermediate Gear Box is a subcomponent of the UH-60 power train system. It is mounted at the base of the tail pylon. It transmits torque and reduces shaft speed from the main module gear box to the tail rotor gear box.

Brief descriptions of the components of interest on the CH-47 Chinook referenced from TM 1-1520-224-10 are:

1. Hinge Pin Assembly is a component of the rotor system. The rotor head consists of a hub connected to three pitch-varying shafts by three horizontal hinge pins. These pins permit blade flapping. Stops on the top and bottom of the hub limit the blade flapping motion.

2. Tie Bar Assembly is located close to the hinge pin assembly. It connects the pitch-varying shafts to the pitch-varying housings on the rotor heads.

3. Engines on the CH-47 are housed in separate nacelles mounted externally on each side of the aft pylon.

4. Forward/Aft Swashplate Bearings rotate and transfer blade pitch changes by the three pitch-varying links to the pitch-varying housing on each rotor blade.

C. MAINTENANCE REGIMES OF COMPONENTS

Army Aviation maintenance regimes are composed of both periodic and on condition maintenance tasks. Prescribed maintenance tasks can be subdivided into five major areas: (AMCOM Proof of Principle, 2005)

1. PM: Maintenance or inspections performed in accordance with normal Preventive Maintenance Checks and Services.

2. On Condition: Maintenance or inspections occurring after the aircraft encounters a specific event or flight in certain environmental conditions.

3. -18: Maintenance or inspections prescribed in maintenance manuals and tracked on the -18 forms kept in the aircraft log book.

4. ASAM: Maintenance or inspections listed in a specific Aviation Safety Action Message.

5. AWR: Maintenance or inspections listed in a specific Air Worthiness Release.

These maintenance tasks are outlined by several different maintenance manuals, log book forms, and messages/releases specific for each airframe type. A component may be inspected as often as every day or at intervals of several hundred hours. Each inspection interval is a unique inspection in the sense that some of the more common inspections are a visual exterior check of a component whereas the more infrequent inspections require removal of the component from the airframe, disassembling it, and conducting a much more thorough inspection. Each inspection has a specific number of maintenance-man hours (MMH) required in order to complete the maintenance task.

Listed below in Tables 4 and 5 are the most time consuming and thorough inspections for each component listed above for the AH-64 Apache and UH-60 Blackhawk. In cases where there are two different interval inspections with the same MMH and clock time requirements the more frequent inspection of the two is listed:

Table 4. AH-64 Apache Maintenance Regime

| AH-64 Component | Inspection Interval | Reference | Maint Type | MMH |
|--|---------------------|----------------------|------------|-------|
| APU Clutch | 250 Flight Hours | TB 1-1520-238-20-139 | -18 | 34.4* |
| Eng Assy, 701C | 500 Flight Hours | TM 1-1520-238-PM | PM | 20.5* |
| Utility Hydraulic Pump | 250 Flight Hours | TB 1-1520-238-20-139 | -18 | 1.1 |
| Forward Hanger Bearing | 500 Flight Hours | TM 1-1520-238-PM | PM | 4.4* |
| Aft Hanger Bearing | 500 Flight Hours | TM 1-1520-238-PM | PM | 4.4* |
| Main Rotor Pitch Housing | 125 Flight Hours | TM 1-1520-238-23 | -18 | 0.5* |
| Main Rotor Upper Mast Bearing | 500 Flight Hours | TM 1-1520-238-PM | PM | 20.4* |
| Main Rotor Lower Mast Bearing | 500 Flight Hours | TM 1-1520-238-PM | PM | 20.4* |
| * If no Maintenance Allocation Chart (MAC) data was available or seemed suspect a review of the appropriate techniques were conducted and a time was allocated by AMCOM Subject Matter Experts | | | | |

Table 5. UH-60 Blackhawk Maintenance Regime

| UH-60 Component | Inspection | Reference | Maint Type | MMH |
|--|------------------|-------------------|------------|-------|
| Oil Cooler Fan Bearing | 700 Flight Hours | TM 1-1520-237-PMI | PM | 11.3* |
| Main Rotor Blade | 700 Flight Hours | TM 1-1520-237-PMI | PM | 17.2 |
| Pump Module Assembly | 700 Flight Hours | TM 1-1520-237-PMI | PM | 0.03 |
| Damper Assembly | 700 Flight Hours | TM 1-1520-237-PMI | PM | 2.5* |
| Engine Assembly, 701C | 700 Flight Hours | TM 1-1520-237-PMI | PM | 12.4* |
| Engine Output Drive Shaft | 700 Flight Hours | TM 1-1520-237-PMI | PM | 4.9* |
| Intermediate Gear Box | 120 Flight Hours | TM 1-1520-237-23 | -18 | 2.0* |
| * If no Maintenance Allocation Chart (MAC) data was available or seemed suspect a review of the appropriate techniques were conducted and a time was allocated by AMCOM Subject Matter Experts | | | | |

A CH-47 Chinook Maintenance Regime is not listed since a Proof of Principle brief was not conducted on the CH-47 Chinook CBM+ program due to the progression of the CH-47 CBM+ program. Proofs of Principle briefs are the source of maintenance regime information for both the AH-64 Apache and UH-60 Blackhawk. (Brown, 2005)

D. FAILURE/AGE REPLACEMENT CHARACTERISTICS OF COMPONENTS

The Aviation and Missile Research, Development, and Engineering Center (AMRDEC) provided data sets for component failure times. The failure times are the occurrences of serious diagnostic symptoms requiring maintenance actions. The data sets are displayed in Microsoft Excel format and each data set consists of twenty-one columns. The twenty-two columns are listed below.

1. WUC: Work Unit Code
2. PN: Part Number of component
3. SN: Serial Number of component
4. EI_SN: End Item Serial Number (aircraft tail number)
5. MODEL: The model of aircraft
6. DATE: Date the action was performed
7. REP_NUM: Repair Number-The number of times the part was removed for a causable removal.
8. CEN: Censored-If 1 then installed and still flying, else 0 and component removed
9. LIFE: If CEN=0, the time on the component since new or last causable removal. If CEN=1, the current time on the component.
10. TSN: Time Since New
11. TSO: Time Since Overhaul
12. NOVH: Number of Overhauls
13. F_TYPE: Type of failure
14. FCODE: Failure Code 001 to 999, the reason the part was removed
15. FAILURE: Narrative for the FCODE
16. FAMILY: The fail code grouped into failure family types.
17. PREV_FC: Failure Code on the previous removal

18. REP_UIC: UIC that repaired the item last or original manufacture if REP_NUM=1.

19. REPAIR: Location name of the UIC that repaired the item last.

20. UIC: Unit Identification Code of removing unit

21. LOC: Location of the UIC

22. SN_PREFX: Serial Number substring as a prefix to perform comparison analysis

In addition to this data, each airframe type has a Technical Manual which states a component's Time Between Overhaul (TBO) and/or component retirement time. These manuals allow the determination of a component's age replacement time if one exists. Listed below in Table 6 are the CBM+ component's estimated mean time between failure (MTBF) and Age Replacement times. The Age Replacement times are derived from the applicable airframes' Technical Manual. The MTBFs listed below are obtained from AMCOM's Proof of Principle briefs prepared in July 2005. (Brown, 2005) The MTBF estimates take into account that some of the data are censored. When both TBO and component retirement times are given by the applicable reference the more restrictive of the two numbers is listed.

Table 6. CBM+ Component MTBF and Age Replacement

| AH-64 Component | MTBF | Age Replacement |
|---|----------------------|-------------------------|
| APU Clutch | 900 Flight Hours | On Condition of Failure |
| Engine Assembly, 701C | 1,304 Flight Hours | 5,000 Flight Hours** |
| Utility Hydraulic Pump | 464 Flight Hours | On Condition of Failure |
| Forward Hanger Bearing | 834 Flight Hours | 2,500 Flight Hours |
| Aft Hanger Bearing | 537 Flight Hours | 2,500 Flight Hours |
| Main Rotor Pitch Housing | 257 Flight Hours | 5,300 Flight Hours |
| Main Rotor Upper Mast Bearing | 1,250 Flight Hours | 1,750 Flight Hours |
| Main Rotor Lower Mast Bearing | 1,250 Flight Hours | 9,400 Flight Hours |
| UH-60 Component | MTBF | Age Replacement |
| Oil Cooler Fan Bearing | 14,425 Flight Hours | 700/2,100 Flight Hours* |
| Main Rotor Blade | 1,594 Flight Hours | 9,600 Flight Hours |
| Pump Module Assembly | 5,969 Flight Hours | On Condition of Failure |
| Damper Assembly | 6,629 Flight Hours | On Condition of Failure |
| Engine Assembly, 701C | 1,342 Flight Hours | 5,000 Flight Hours** |
| Engine Output Drive Shaft | 2,581 Flight Hours | On Condition of Failure |
| Intermediate Gear Box | 6,624 Flight Hours | On Condition of Failure |
| CH-47 Component | MTBF | Age Replacement |
| Hinge Pin Assembly | 3,393 Flight Hours | 1,200 Flight Hours |
| Tie Bar Assembly | 2,925 Flight Hours | 4,800 Flight Hours |
| Engine | 602 Flight Hours | 2,400 Flight Hours |
| Forward/Aft Swashplate Bearings | 991/867 Flight Hours | 1,200 Flight Hours |
| *700 flight hours when installed at Station 410.5; all others 2,100 flight hours | | |
| **701C Engine Assembly has several components changed at various intervals. 5,000 Flight Hours is the most common age replacement time of the most critical components. | | |

E. COSTS ASSOCIATED WITH COMPONENTS

Listed below are each component's cost and an estimate of its shipping cost. It is assumed that the components can be divided into three different weight classifications. A component weight is considered to be either *light*, *medium*, or *heavy*. In addition, the component's shipment is either urgent or not urgent. Table 7 displays the approximate costs of shipping components of different weights 2000 miles under urgent and not urgent requirements. These shipping costs, while approximate, are realistic. Although the model and simulation do not include costs for component shipping this must occur in both the Legacy and CBM+ Process; it is important to state these values in recognition that this exists in both processes.

Table 7. CBM+ Component and Shipping Costs

| AH-64 Component | FEDLOG Unit Price | OSMIS Weight | Weight Classification | Urgent Shipping Cost | Non-urgent Shipping Cost |
|---------------------------------|------------------------------|-------------------------|----------------------------------|---------------------------------|---|
| APU Clutch | \$27,774.00 | Unavailable | Medium | \$1,000 | \$500 |
| Engine Assembly, 701C | \$720,974.00 | Unavailable | Heavy | \$3,000 | \$1,500 |
| Utility Hydraulic Pump | \$9,437.00 | Unavailable | Medium | \$1,000 | \$500 |
| Forward Hanger Bearing | \$6,941.00 | 400 | Light | \$200 | \$50 |
| Aft Hanger Bearing | \$5,673.00 | 216 | Light | \$200 | \$50 |
| Main Rotor Pitch Housing | \$6,846.00 | 894 | Medium | \$1,000 | \$500 |
| Main Rotor Upper Mast Bearing | \$7,295.00 | 275 | Light | \$200 | \$50 |
| Main Rotor Lower Mast Bearing | \$5,126.84 | 40 | Light | \$200 | \$50 |
| UH-60 Component | FEDLOG Unit Price | OSMIS Weight | Weight Classification | Urgent Shipping Cost | Non-urgent Shipping Cost |
| Oil Cooler Fan Bearing | \$290.71 | 8 | Light | \$200 | \$50 |
| Main Rotor Blade | \$130,420.00 | 6500 | Medium | \$1,000 | \$500 |
| Pump Module Assembly | \$16,771.00 | 560 | Medium | \$1,000 | \$500 |
| Damper Assembly | \$9,770.00 | 500 | Light | \$200 | \$50 |
| Engine Assembly, 701C | \$720,974.00 | Unavailable | Heavy | \$3,000 | \$1,500 |
| Engine Output Drive Shaft | \$4,812.00 | Unavailable | Medium | \$1,000 | \$500 |
| Intermediate Gear Box | \$20,694.00 | 800 | Medium | \$1,000 | \$500 |
| CH-47 Component | FEDLOG Unit Price | OSMIS Weight | Weight Classification | Urgent Shipping Cost | Non-urgent Shipping Cost |
| Hinge Pin Assembly | \$5,520.00 | 330 | Light | \$200 | \$50 |
| Tie Bar Assembly | \$11,822.00 | 120 | Light | \$200 | \$50 |
| Engine | \$916,406.00 | 11,650 | Heavy | \$3,000 | \$1,500 |
| Forward/Aft Swashplate Bearings | Unavailable | Unavailable | Light | \$200 | \$50 |

III. STOCHASTIC MODELS FOR COMPARING LEGACY MAINTENANCE AND CONDITION-BASED MAINTENANCE PLUS

A. IMPORTANT FACTORS FOR CBM+ CANDIDACY

In determining a whether or not to introduce a component into the CBM+ program a number of factors should be considered:

1. How often does the component fail during active flight hours?

It is preferable to introduce a component that fails often versus components that rarely fail.

2. What are the consequences of a component failing?

It is preferable to introduce a component that possesses severe consequences for failure versus a component that is inconsequential in its failure.

3. What is the difficulty level of the inspection that would be alleviated by CBM+?

If an inspection is extremely difficult and resource intensive to perform it would be preferable to have this inspection replaced by CBM+ versus an inspection that is simple and easy to perform.

4. Is a CBM+ sensor feasible for a component?

If measurements cannot be taken to assess the degradation of the component before it fails then that component would not be a good CBM+ candidate. Furthermore, the time from occurrence of measurable evidence of impending failure until failure should be long enough to detect the impending failure and take maintenance action.

5. What is the reliability of the CBM+ sensor, the difficulty of inspecting the CBM+ sensor, and the effect of the CBM+ sensor on performance of the component being monitored? Is there even a CBM+ sensor currently developed for a component? What is the cost of the sensor?

By focusing on the CBM+ sensor it can be determined whether or not the sensor itself may sometimes miss impending failures, give false positives, require intensive

maintenance, or impede standard operations. Maintainers are often wary of adding a new system designed to help them conduct maintenance operations for fear of there now being one more system to maintain.

Stochastic models can be created to assist in identifying information needed to determine characteristics of components that make the component a good candidate for monitoring by CBM+. Such stochastic models compare a single component's performance and associated costs in both the CBM+ and Legacy processes. The models can vary in detail and complexity; transparency and simplicity are desirable.

B. MODEL OVERVIEW

In choosing a model to represent the operating environment of CBM+ it is convenient to let every aircraft component being considered for CBM+ begin in good operating condition. Over time the component's condition/state degrades and eventually the component fails. We consider a component that allows predictive measurements to be made of its condition (failure propensity); these are diagnostic symptoms (DS). If a DS can be recognized by maintenance personnel then this information is a useful indication that the component is beginning to fail. A DS can be detected by a CBM+ sensor or noticed by a maintainer during the conduct of scheduled maintenance, or by the operator.

If conditions for a near-term future failure exist it is essential to recognize the impending failure in order to lessen such a failure's effect. CBM+ sensors recognize impending failure of components by monitoring the component's performance. Specifically the UH-60 IMD-HUMS system notes condition indicators (CIs) based on vibratory analysis of items such as bearings, shafts, and gears. These CIs are rolled up into health indicators (HIs) which are numbers from 0 to 1 displaying the perceived health of that component. (Wright, 2005) This system of CIs and HIs is used to determine the occurrence of DSs. Under the Legacy maintenance system when maintenance personnel conduct a scheduled inspection of an aircraft they are looking for chips, cracks, dents, nicks, wears, incorrect lubrication levels, incorrect pressure outputs (pneumatic and fluids), and other potential faults. These physical inspections determine

the occurrence of DSs. A DS may or may not be noticed during the downtime immediately following the mission during which it was generated. All DSs are discovered during inspections during downtimes. (Gaver and Jacobs, 2006)

The following are the components which form a general framework for a Non-Homogeneous Poisson Process (NHPP) model for the occurrence of DSs for both the CBM+ process and the Legacy process:

$N(t)$: number of transitions of components from good condition to poor condition during the time interval $(0, t]$, (number of occurrences of DSs during $(0, t]$); each transition corresponds to the occurrence of one DS. In many cases the times between failures of repairable components may tend to decrease as the components age. Thus $\{N(t); t \geq 0\}$ is assumed to be a nonhomogeneous Poisson process with

$\Lambda(t)$: mean value function of $\{N(t); t \geq 0\}$; that is $E[N(t)] = \Lambda(t)$.

$\lambda(t)$: intensity function of $\{N(t); t \geq 0\}$; that is $\lambda(t) = \frac{d\Lambda(t)}{dt}$.

m : constant mission length

C. A NON-HOMOGENEOUS POISSON PROCESS (NHPP) MODEL

Renewal processes are often used to model times between failures for a system. For a renewal process to apply, the times between successive failures should be independent and identically distributed with an arbitrary distribution. (Ross, 2003) In order to either accept or refute the assumption that the times between failures are independent and identically distributed failure data must be analyzed. The data set that was selected for evaluation is the set of AH-64/UH-60 701C Engine lifetime data. The lifetimes are the times between occurrences of serious diagnostic symptoms requiring maintenance action. The reason for the selection of this data set is that each engine may have several failure times recorded. The data set contains both censored and uncensored lifetime data. Multiple lifetimes for an engine are indicated by the same engine serial number (SN) being listed with consecutive lifetimes (REP_NUM). This gives the

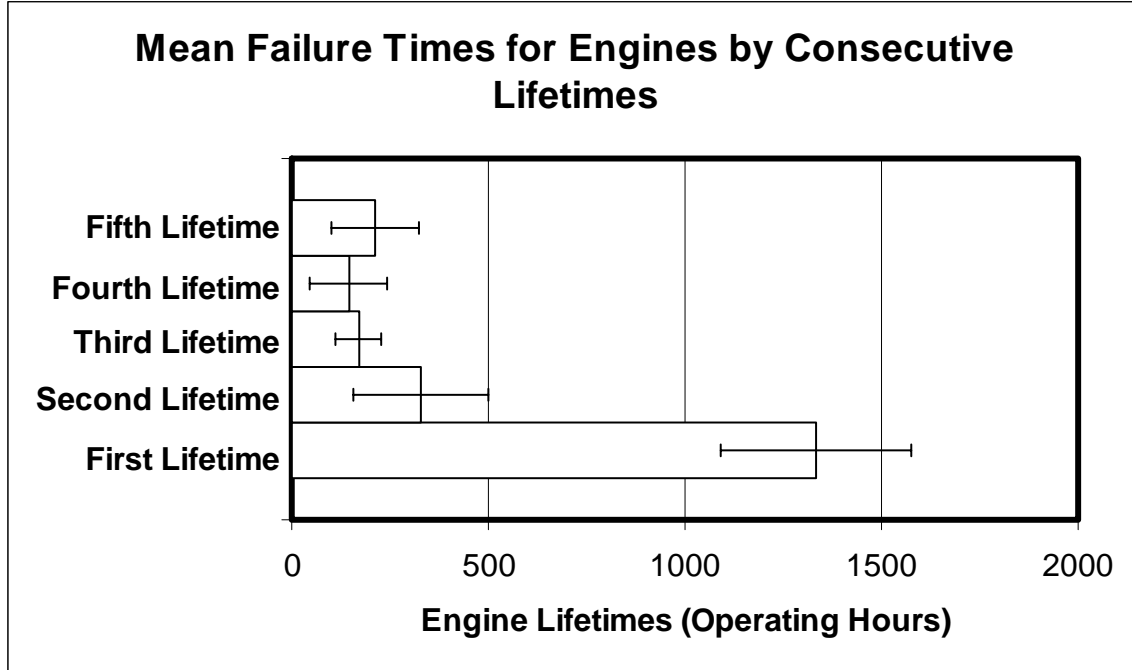
opportunity to assess whether or not the successive times between failures for an engine can be approximately represented as independent and identically distributed. If there is evidence that the successive lifetimes are not independent and identically distributed, then a renewal process model for the times between failures is not appropriate.

Analysis of the engine data suggests that the times between failures are not identically distributed. Therefore a Non-Homogeneous Poisson Process (NHPP) model for the failure times is considered. Although the term “failure” is used, these events are actually occurrences of serious diagnostic symptoms that require maintenance action.

The AH-64/UH-60 701C Engine data provided by AMRDEC consists of 3,385 entries in the format outlined in Chapter Two. From this group of 3,385 entries there were 2,045 entries that were first lifetimes, 913 entries that were second lifetimes, 480 that were third lifetimes, and 397 that were fourth lifetimes. These data are not complete with regards to all lifetimes being annotated for all serial numbers. There are missing lifetime data which are not due to censoring. However, some of these missing lifetimes can be inferred from other recorded data. For example, suppose the first lifetime is missing but the second lifetime is recorded along with the time since the engine was new at the time of the second failure. In this case the first lifetime can be inferred by subtracting the second lifetime from the time since new. The engine data considered appear in Appendix A. The engines considered have at least three failure times recorded. The columns named WUC, PN, TSO, NOVH, REP_UIC, REPAIR, UIC, LOC, and SN_PREFIX have been omitted from the original data set since these factors are not relevant in this analysis, and to make the data set more compact. None of the engines displayed TSO (Time Since Overhaul) and NOVH (Number of Overhauls); therefore these columns are omitted.

In Figure 4 the mean times between failures for the first, second, third and fourth failures with 95% confidence intervals are displayed; censored lifetimes are not included. This figure suggests that the successive lifetimes of an engine are not identically distributed; the time until first failure tends to be much larger than the subsequent times between failures.

Figure 4. Mean Failure Times for Engines by Consecutive Lifetimes



An estimate of the intensity function of a NHPP is obtained by using disjoint time intervals of length 500 hours from 0 to 3,000 hours. Let $N_j(t)$ be the number of failures for engine j during the time interval $(0, t]$.

$$I_j(x, \infty) = \begin{cases} 1 & \text{if the last observation for engine } j \text{ (censored or not) is greater than } x \\ 0 & \text{otherwise} \end{cases}$$

The intensity function in the age interval $[x, x+500]$ where $x \in (0, 500, 1,000, 1,500, \text{etc.})$ is estimated as

$$\frac{\sum_j [N_j(500+x) - N_j(x)]}{500 \sum_j I_j(x)} \quad (\text{Jacobs, 2006})$$

A display of the resulting estimated intensity function is in Appendix B. The log of the estimated intensity function versus $\log t$ is also displayed. This latter display suggests that an NHPP with power-law mean value function $\Lambda(t) = \gamma t^\delta$ tends to summarize the data well. The parameters of a NHPP with power-law mean value function of the form

$\Lambda(t) = \gamma t^\delta$ are estimated from the engine data using maximum likelihood. The estimates and standard errors are listed in Figure 5. The standard errors are obtained using Fisher information. (Bickel and Doksum, 1977)

Figure 5. NHPP Parameter Estimates

| NHPP Parameter Estimates | | | |
|--------------------------|--|-----------------------|--------------|
| Estimate of γ | 5.4×10^{-6} | Estimate of δ | 1.71 |
| Standard Error | 6.3×10^{-7} | Standard Error | 0.015 |
| Estimate ± 2 s.e. | $(4.2 \times 10^{-6}, 6.7 \times 10^{-6})$ | Estimate ± 2 s.e. | (1.68, 1.74) |

The estimate of δ is statistically significantly greater than 1, suggesting that failures are more frequent for older engines. The older an engine, the more likely various subcomponents are to fail.

D. MODEL STRUCTURE

The power law NHPP model with the estimated parameters is used in a model to assist in the selection of components for inclusion in the CBM+ process. The model represents the arrival of DSs during each mission, the number of downtimes elapsed until the DSs are discovered, the repair times associated with the discovery of the DSs, and the chance a component failure will cause a mission abort. This analytical model is taken directly from Gaver and Jacobs (2006).

Let $N(t)$ be the number of transitions of components from good condition to poor condition (occurrence of diagnostic symptoms (DS)) during the operational time interval $(0, t]$. $\{N(t); t \geq 0\}$ is a nonhomogeneous Poisson process with mean value function

$\Lambda(t) = E[N(t)]$ and intensity function $\lambda(t) = \frac{d\Lambda(t)}{dt}$. The DSs may not be discovered

immediately. The DSs are discovered during inspection during downtimes. Each mission is of length m . Let $N_i = N(mi) - N(m(i-1))$ be the number of DSs to occur during the i th mission. N_i has a Poisson distribution with mean $\Lambda_i = \Lambda(mi) - \Lambda(m(i-1))$. For example if the length of the mission is 4 hours long ($m=4$) and $\Lambda(t) = \gamma t^\delta$, then

$\Lambda_i = \gamma(4i)^\delta - \gamma(4(i-1))^\delta$. The computations used to derive the estimates of γ and δ are listed in Appendix C. These estimated values are used throughout the thesis.

Let p_j be the conditional probability a DS is discovered during the j th downtime after the mission within which it first appears, given it has not been discovered before and the DS has not caused a mission abort; the downtime immediately after the mission the DS appears in is labeled downtime 1. In general, $p_1 \leq p_2 \leq \dots$. Assume that whether or not a DS is discovered during a downtime is independent from downtime to downtime and from DS to DS. Suppose also that if a DS is generated during a mission it can critically activate during that mission, causing the mission to fail. This is known as a mission abort. Further, let a_j denote the conditional probability that the DS critically activates during the j th mission after its generation, given it has not been discovered and rectified in advance; a_1 is the probability of critical activation during the mission of its genesis. Let $\mathbf{D}_{i,i+j}$ be the number of DSs that occurred during mission i that are discovered during the j th downtime after mission i before a critical activation; it has a Poisson distribution with mean $\Lambda_i \left[\prod_{k=1}^{j-1} (1-p_k)(1-a_k) \right] (1-a_j) p_j$; that is, $\mathbf{D}_{i,i}$ has a Poisson distribution with mean $\Lambda_i (1-a_1) p_1$; $\mathbf{D}_{i,i+1}$ has a Poisson distribution with mean $\Lambda_i (1-a_1)(1-p_1)(1-a_2) p_2$, etc. Further, these random variables are currently assumed independent. It is of course possible that critical activation occurs before the DS is discovered and the fault removed. Let $\mathbf{D}_{i,i+j}^*$ denote the number of DSs that are generated during the i th mission that give rise to a critical activation (mission abort) before discovery j missions after they are generated. Clearly $\mathbf{D}_{i,i}^*$ is Poisson with mean $\Lambda_i a_1$, $\mathbf{D}_{i,i+1}^*$ is Poisson with mean $\Lambda_i (1-a_1)(1-p_1) a_2$; etc. (Gaver and Jacobs, 2006)

Assume that DSs that cause mission abort are discovered in the downtime following the aborted mission. The number of DSs discovered during the i th downtime,

$$\tilde{\mathbf{D}}_i = \sum_{j=1}^i \left[\mathbf{D}_{j,j+(i-j)} + \mathbf{D}_{j,j+(i-j)}^* \right], \text{ has a Poisson distribution with mean}$$

$$E[\tilde{D}_i] = \sum_{j=1}^i \Lambda_j \left[\prod_{k=1}^{(i-j)} (1-p_k)(1-a_k) \right] \left[1 - (1-a_{i+1-j})(1-p_{i+1-j}) \right]$$

where an empty product is interpreted as equal to 1. (Gaver and Jacobs, 2006)

The expected number of missions that are not aborted during the first t scheduled missions can be calculated as follows. Let $S(t)$ be the number of DSs that can cause mission abort during mission t ; there is at most one mission abort per mission. Let $s(n)$ be the probability a DS causes a mission abortion during the n th mission after it is generated. Assume $p_i \equiv p$ and $a_i \equiv a$ for all i .

$$s(n) = [(1-a)(1-p)]^{n-1} a \quad (1)$$

$$E[S(t)] = \sum_{i=1}^t \Lambda_i s(t-(i-1))$$

$$Var[S(t)] = \sum_{i=1}^t \Lambda_i s(t-(i-1))$$

$S(t)$ has a Poisson distribution. The probability mission t is aborted is $P\{S(t) > 0\} = 1 - \exp\{-E[S(t)]\}$. Let $A(t)$ be the number of missions that have been aborted during the first t missions. A mission is aborted if at least one DS causes a mission abort.

$$E[A(t)] = \sum_{i=1}^t [1 - \exp\{-E[S(i)]\}] \quad (2)$$

$$VAR[A(t)] = \sum_{i=1}^t [1 - \exp\{-E[S(i)]\}] \exp\{-E[S(i)]\}$$

In the general case

$$s(t) = \prod_{i=1}^{t-1} [(1-a_i)(1-p_i)] a_t \quad (3)$$

where an empty product is set equal to 1. (Gaver and Jacobs, 2006)

IV. LEGACY MAINTENANCE AND CONDITION-BASED MAINTENANCE PLUS SIMULATION

A. SIMULATION ARCHITECTURE AND CHARACTERISTICS

This simulation is based on the nonhomogeneous Poisson process model as described in Chapter III. The Visual Basic for Applications (VBA) coding used as a macro within Microsoft Excel 2003 is listed in Appendix D. The Excel workbook consists of four worksheets named “RVs,” “Legacy Process,” “CBM+ Process,” and “Data.”

The purpose of “RVs” worksheet is to receive all variable inputs. The variable inputs for this simulation are:

1. # Replications: This number sets the number of iterations for the simulation to perform.
2. $P_L(h)$: The probability that the Legacy Process will recognize a DS during a downtime that includes an inspection lasting h hours.
3. P_C : The probability that the CBM+ Process will recognize a DS during a downtime. The number of downtimes until a DS is discovered has a geometric distribution with mean $\frac{1}{P_C}$. For each DS an independent P_C is drawn from a Beta distribution with mean 0.99 and variance .00037711. The randomization of P_C is determined by a Beta distribution and both α_B and β_B parameters are entered on the worksheet. Initially the Beta distribution is generated using $\alpha_B=25$ and $\beta_B=.25$. The equation for the probability density function of the beta distribution is:

$$f(x; \alpha_B, \beta_B) = \frac{1}{B(\alpha_B, \beta_B)} x^{\alpha_B-1} (1-x)^{\beta_B-1} \text{ for } 0 \leq x \leq 1 \text{ and } 0 \text{ otherwise}$$

where B is the normalizing constant.

4. R_0 : The initial repair time incurred upon a DS discovery.
5. R_1 : The subsequent repair time incurred if DS not discovered after first mission.

6. A_0 : The initial repair time incurred upon a mission abort.

7. A_1 : The subsequent repair time incurred if mission abort causing DS is not discovered after first mission.

8. M_A : For each DS an independent time until the DS results in a mission abort is drawn from a Weibull distribution with shape parameter 1.5 and mean 10. The values of both Weibull parameters α_W and β_W parameters are entered on the worksheet. Initially the Weibull distribution is generated using $\alpha_W=1.5$ and $\beta_W=11.08$. The equation for the probability density function of the Weibull distribution is:

$$f(x; \alpha_W, \beta_W) = \left(\frac{\alpha_W}{\beta_W}\right) \left(\frac{x}{\beta_W}\right)^{(\alpha_W-1)} e^{-\left(\frac{x}{\beta_W}\right)^{\alpha_W}} \quad \text{for } x \geq 0 \text{ and } 0 \text{ otherwise} .$$

9. P_{OH} : This is the probability that the required replacement component is on hand when a DS is discovered or causes mission abort. For each discovered DS, or a DS that causes a mission abort, an independent Bernoulli random number is generated to determine if the replacement component is immediately available or must be ordered from a depot.

10. T_{OH} : If a replacement component is ordered, a time T_{OH} until the replacement component arrives is generated; the time has an exponential distribution.

11. λ_i : The expected number of DSs to occur during mission i having length 4 hours; $\lambda_i = \gamma[(4i)^\delta - (4(i-1)^\delta)]$; the values of gamma and delta are the maximum likelihood estimates obtained from analysis of the engine data.

The “RVs” worksheet generates the number of DSs to occur during each mission; the number of DSs that occur during the i^{th} mission is generated using a Poisson distribution where the mean is determined by the appropriate λ_i . These numbers of DSs are used for both the “Legacy Process” and the “CBM+ Process.” This provides a common arrival process for both the Legacy and CBM+ processes.

The purpose of the “Legacy Process” and “CBM+ Process” worksheets is to provide the cell structure and formula to determine the following information for the two different processes:

1. D_{ij} : The number of downtimes to occur until the j th DS generated during the i th mission is discovered.

2. M_{Aij} : The number of downtimes to occur until the j th DS generated during the i th mission results in a mission abort; for each DS the same time until mission abort is used in the Legacy and CBM+ models.

3. R_{ij} : The total repair time from the j th DS resulting from the i th mission.

4. S_{ij} : The total time awaiting replacement components from the j th DS resulting from the i th mission; for each DS the time is drawn from an exponential distribution with a common mean for both the Legacy and CBM+ models.

The purpose of the “Data” worksheet is to display the results of each simulation replication and then compute the means, standard deviations, and 95% confidence intervals of the results for the Legacy and CBM+ processes. The results that are tabulated for both processes are:

1. $\sum DS_{s \leq M}$: The number of diagnostic symptoms that are detected before the end of the total number of missions observed (M).

2. $\sum DS_{s > M}$: The number of diagnostic symptoms that are detected after the end of the total number of missions observed (M) but were generated during the M missions.

3. $\sum Aborts_{\leq M}$: The number of mission aborts that occur before the end of the total number of missions observed (M).

4. $\sum Aborts_{> M}$: The number of mission aborts that occur after the end of the total number of missions observed (M) that are due to DSs generated during the M missions.

5. $\sum R_{\leq M}$: The sum of repair times that occur before the end of the total number of missions observed (M).

6. $\sum R_{> M}$: The sum of repair times that occur after the end of the total number of missions observed (M) that are due to DS generated during the M missions.

7. $\sum R$: The sum of repair times that occur.

8. $\sum S_{\leq M}$: The sum of time spent awaiting component arrival that occurs before the end of the total number of missions observed (M).

9. $\sum S > M$: The sum of time spent awaiting component arrival that occurs after the end of the total number of missions observed (M) that are due to DS generated during the M missions.

10. $\sum S$: The sum of time spent awaiting component arrival that occurs.

B. DETERMINATION OF P_C AND P_L

The number of downtimes until the Legacy or CBM+ process recognizes a DS is a direct result of a process's probability of successfully at detecting a DS. The conditional probability a DS is discovered n downtimes after it is generated in the Legacy process, given it has not been discovered before and has not caused a mission abort, is $P_L(h)$ where h is the maintenance man-hours (MMH) incurred during the downtime; in the CBM+ process the conditional probability a DS is discovered during a downtime, given it has not been discovered before and has not caused a mission abort is a constant P_C ; that is the number of downtimes until a generated DS is discovered has a geometric distribution with probability of success P_C . Initially it is assumed that the CBM+ Process P_C has an expected value of 0.99; this may be an optimistic value. The effect of the variability of the time to discover different DSs is modeled by randomizing P_C using a Beta distribution. For each generated DS the P_C is independently drawn from a Beta distribution having mean 0.99. The mean value of 0.99 is based on a telephone conversation with Mr. Johnny Wright the Deputy Program Manger for B.F. Goodrich Corporation's IMD-HUMS program on January 27, 2006. (Wright, Personal Communication, 2006) He stated that the parameters of the CBM+ sensors were set very conservatively in order to capture all changes in vibratory patterns. Since this is an emerging technology, B.F. Goodrich Corporation wants to ensure that their sensors do not inadvertently miss any vibratory indications that could be used to indicate impending component failure. However, the conservative setting may increase the chance of false alarms. The mean value of P_C will be varied in Chapter 5 in order to explore sensitivity of the simulation results to its value. Furthermore false positives (false alarms) will also be introduced into the simulation in order to observe their impact on the CBM+ process.

The Legacy maintenance schedule of the UH-60 Blackhawk 701C Engine Assembly will be used to describe the specification of the probabilities of the Legacy system discovering a previously generated DS during the downtime with h MMH, $P_L(h)$. Although the 701C Engine Assembly is used by both the AH-64 Apache and the UH-60 Blackhawk the two airframes have different maintenance schedules. Listed in Table 8 below is the maintenance schedule for the UH-60 Blackhawk 701C Engine Assembly maintenance schedule as listed in the AMCOM Proof of Principle briefing from June of 2005. (Brown, 2005)

Table 8. UH-60 Blackhawk 701C Engine Assembly Maintenance Regime

| Inspection | Reference | Maint Type | Task or Paragraph | MMH |
|--------------------------------|-------------------|------------|-------------------|------|
| Pre-Flight | TM 1-1520-237-CL | PM | Not Applicable | 0.1 |
| Post-Flight | TM 1-1520-237-CL | PM | Not Applicable | - |
| Daily | TM 1-1520-237-PMD | PM | 6.17 | 0.2 |
| 40 Hr Output Shaft Inspection | TM 1-1520-237-23 | PM | ch 1 sec 7-10.2 | 0.4 |
| 120 Hr DS Inspection | TM 1-1520-237-23 | -18 | ch 1 sec 7-11.1 | 3.4 |
| 120 Hr Clean Engine Compressor | TM 1-2840-248-23 | -18 | 1.158 thru 1.161 | 1.6 |
| 350 Hr | TM 1-1520-237-PMI | PM | 6.37, 6.43 | 5.9 |
| 700 Hr | TM 1-1520-237-PMI | PM | 6.37 - 6.48 | 12.4 |

It is evident that the most time intensive inspection occurs every 700 hours and it requires 12.4 maintenance man-hours (MMH). 12.4 MMH is the h_{max} . We assume the probability of detecting a DS during this inspection is $P_L(700) = P_C$. We assume that the amount of MMH expended during an inspection, h , is an indication of the probability of discovering a DS of $P_L(h)$. We model the probability of detecting a DS for the other inspections as follows:

1. Set $x^{h_{max}} = 1 - P_L(h_{max})$ for the known most MMH-intensive inspection;
2. Solve for $x = (1 - P_L(h_{max}))^{\frac{1}{h_{max}}}$;

3. The probability of detecting a DS during an inspection lasting h hours is

$$P_L(h) = 1 - (1 - P_L(h_{\max}))^{\frac{h}{h_{\max}}}.$$

Using this methodology and Table 8 the following values are computed for $P_L(h)$ at differing maintenance inspection intervals.

Table 9. UH-60 Blackhawk 701C Engine Assembly P_L

| Inspection Interval | Maintenance Man-Hours | $P_L(h)$ |
|---|-----------------------|----------|
| Baseline* | 0.3 | 0.11 |
| 40 Hour | 0.4 | 0.14 |
| 120 Hour | 5 | 0.84 |
| 350 Hour | 5.9 | 0.89 |
| 700 Hour | 12.4 | 0.99 |
| * Baseline is summed total of Pre/PostFlight and Daily inspection times | | |

This provides realistic models of varying levels of $P_L(h)$ that can be input into the simulation. The generation of the times until DS discovery for both processes is detailed in Section D below.

C. ANALYTICAL VERSUS STOCHASTIC RESULTS

Results obtained from the simulation and the analytical formulas are displayed in Table 10. Examination of the results can determine whether or not the simulation model and the analytical model results are comparable. Since DS arrivals drive all other factors in this simulation it is important to evaluate the number of DS arrivals during the course of 1,250 missions (5,000 flight hours). The expected number of DSs that are generated during 1250 missions is $\gamma 5000^\delta = 11.42$ where $\gamma = 5.4 \cdot 10^{-6}$ and $\delta = 1.71$. The simulation model with 1,000 replications results in a mean number of DSs generated equal to 11.34 with a 95% confidence interval of (11.14, 11.54). Thus the generation of DSs in the analytical model and the simulation are in good statistical agreement.

Results from a simulation of the number of mission aborts during 500 missions are displayed in Table 10. Each simulation has 500 replications. The time until a DS is

discovered has a geometric distribution with constant probability of success P_C . The time until a DS causes a mission abort has a geometric distribution with probability of success P_A ; the two times are assumed independent. The mean number of system aborts and the corresponding expected number of system aborts obtained from the analytical model equations (1) and (2) are displayed. As expected the analytical results fall within the 95% confidence interval of the simulation results.

Table 10. Special Case Analytical and Simulation Results

| <u>Case</u> | <u>Analytical</u> | <u>Simulation (95% CI)</u> |
|--------------------|--------------------------|-----------------------------------|
| $P_C=.7, P_A=.1$ | 5.99 | 6.02 (5.87, 6.17) |
| $P_C=.7, P_A=.2$ | 11.44 | 11.60 (11.40, 11.80) |
| $P_L=.3, P_A=.2$ | 19.50 | 19.77 (19.49, 20.05) |

D. RANDOM NUMBER GENERATION USING CRYSTAL BALL

The add-in Crystal Ball version 5.5 is used as the random number generator (RNG) for this simulation. Crystal Ball version 5.5 is chosen to provide the random numbers for this simulation because Microsoft Excel 2003's RNG has been shown to have insufficient period length and an incorrect implementation of the Wichmann-Hill Algorithm. (McCullough and Wilson, 2005) Crystal Ball is considered one of the industry's leading edge Monte Carlo simulation add-ins for Excel. It uses a multiplicative congruential generator that has a stream of $2^{31}-1$ pseudo random numbers before repeating. The iteration formula uses the multiplier 62089911. Crystal Ball produces a cycle of random numbers that repeats only after several billion trials. (Decisioneering, 2005)

The times until detection of DSs are generated for the CBM+ process by drawing a random variable from an exponential distribution with a mean of 1 and multiplying that value by $\frac{1}{\theta_c}$ then rounding the value up to the next integer; θ_c is equal to $-\ln(1-P_C)$.

This gives the number of downtimes until the DS is discovered. If the downtime is one, the DS is discovered during the downtime immediately following the mission during

which it was generated. The generation for $\theta_L(h)$ is based on the maintenance schedule for the component. For example if an arduous inspection occurs every fifty operating hours then that is reflected in an increase in the probability a DS is discovered, $P_L(h)$, and subsequently $\theta_L(h) = -\ln(1 - P_L(h))$. The time until detection of a DS for the Legacy process is determined by generating an exponential random variable with mean 1, Y , and determining the smallest n such that $Y \leq \theta_L(h_1) + \dots + \theta_L(h_n)$ where h_n is the MMH of the n th inspection after generation of the DS with h_1 being the MMH for the inspection following the mission the DS is generated in. A common independent exponential random variable with a mean of 1 is used to generate the time until DS discovery for the Legacy process and for the CBM+ process. The operational time until a DS causes a mission abort is generated by drawing an independent random variable from a Weibull distribution. Since the Weibull distribution is a continuous distribution the value is rounded up to the nearest whole number. The time until mission abort and the time until DS discovery are then compared and whichever event occurs first is the event that happens; the other event is ignored. If the two discrete times are equal, the mission is aborted. N_i is the number of DSs that originate in a given mission (i). The simulation is designed so that the N_i is identical for both the Legacy and CBM+ processes. Crystal Ball uses the method of inverse transformation to generate both the Exponential and Weibull random variables. (Decisioneering, 2005)

V. DATA ANALYSIS

A. VARYING CBM+ SENSOR EFFICIENCY

One of the measures to evaluate a component for selection to the CBM+ process is the level of CBM+ sensor efficiency. In particular how effective must a CBM+ sensor be in discovering DSs to result in a smaller number of aborted missions compared to that of the Legacy process. Varying sensor efficiency is defined as varying the mean probability of successfully discovering a particular DS, P_C , in the simulation. Appendix E contains tables displaying the statistical summaries of the simulation output for the Legacy and CBM+ processes as the CBM+ sensor efficiency mean value is varied from 0.99 to 0.1. The value of P_C for each generated DS is determined by an independent draw from a Beta distribution. Table 11 displays the beta parameter values used in the simulation.

Table 11. P_C Beta Distribution Parameters

| <u>E(X)=P_C</u> | <u>VAR(X)</u> | <u>α_B</u> | <u>β_B</u> |
|---------------------------|---------------|----------------------|----------------------|
| 0.99 | 0.00037711 | 25 | 0.25252525 |
| 0.90 | 0.00312741 | 25 | 2.77777777 |
| 0.80 | 0.00496124 | 25 | 6.25 |
| 0.70 | 0.00571984 | 25 | 10.71428571 |
| 0.60 | 0.00562500 | 25 | 16.66666666 |
| 0.50 | 0.00490196 | 25 | 25 |
| 0.40 | 0.00377953 | 25 | 37.5 |
| 0.30 | 0.00249012 | 25 | 58.33333333 |
| 0.20 | 0.00126984 | 25 | 100 |
| 0.10 | 0.00035857 | 25 | 225 |

The time until a DS causes a mission abort has a Weibull distribution with mean 10 and shape parameter $\alpha_w=1.5$. The number of replications in the simulation is set to 1000. Although P_C is randomized for each DS for the CBM+ process, the values of $P_L(h)$ are not randomized for the Legacy process and therefore the only changes in the Legacy process observed between simulations of different P_C s are due to the variability inherent in the stochastic nature of the simulation. In Appendix E the statistical summaries of the

simulation output are displayed and indicate very small standard errors for the estimates of mean number of mission aborts in the following graphs.

Figure 6. Mean Number of Mission Aborts out of 1,250 Missions when time until Mission Aborts has a Weibull distribution with mean 10 and $\alpha_W=1.5$

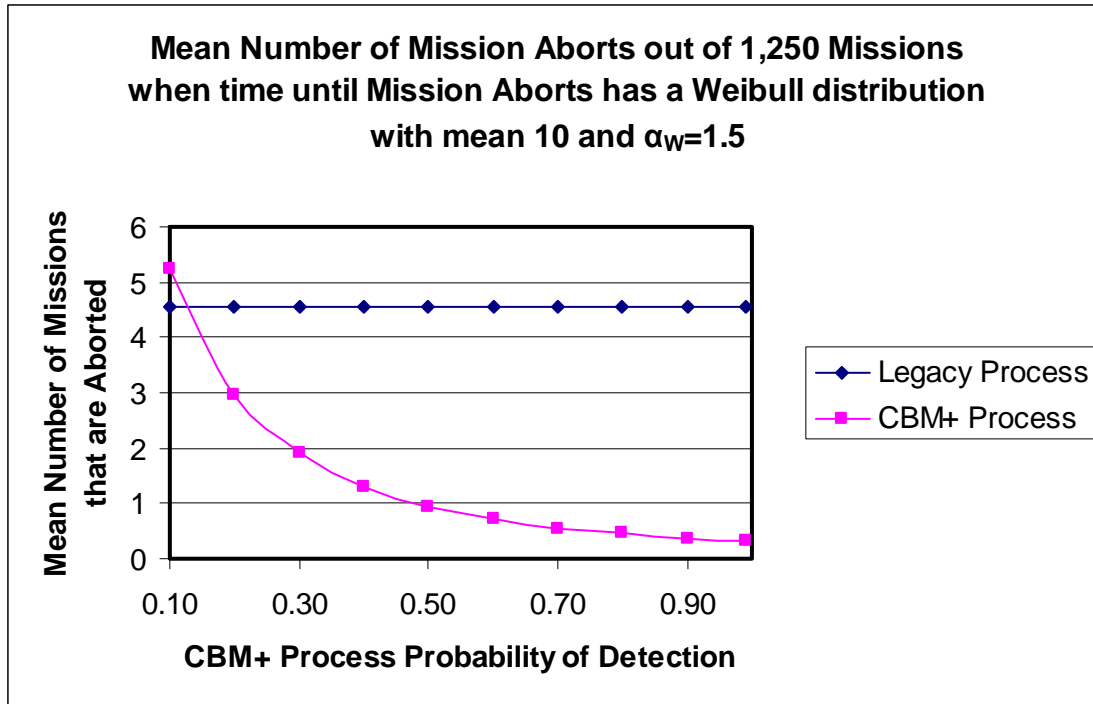
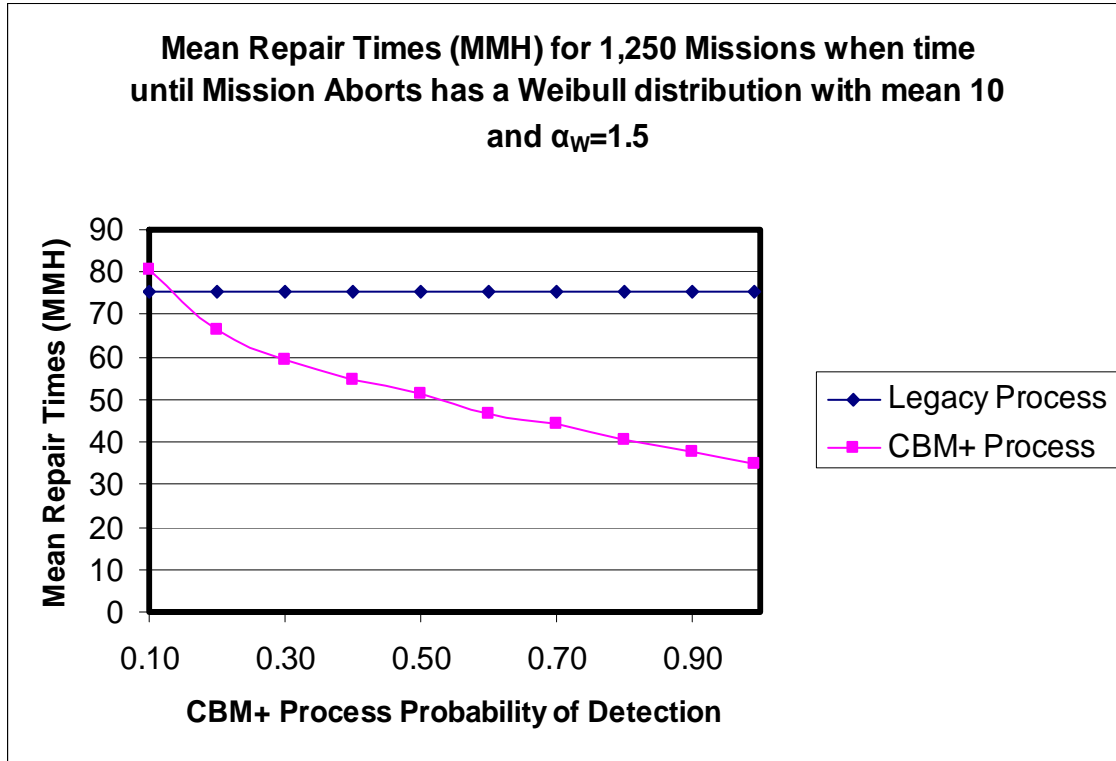


Figure 7. Mean Repair Times for 1,250 Missions when time until Mission Aborts has a Weibull distribution with mean 10 and $\alpha_W=1.5$



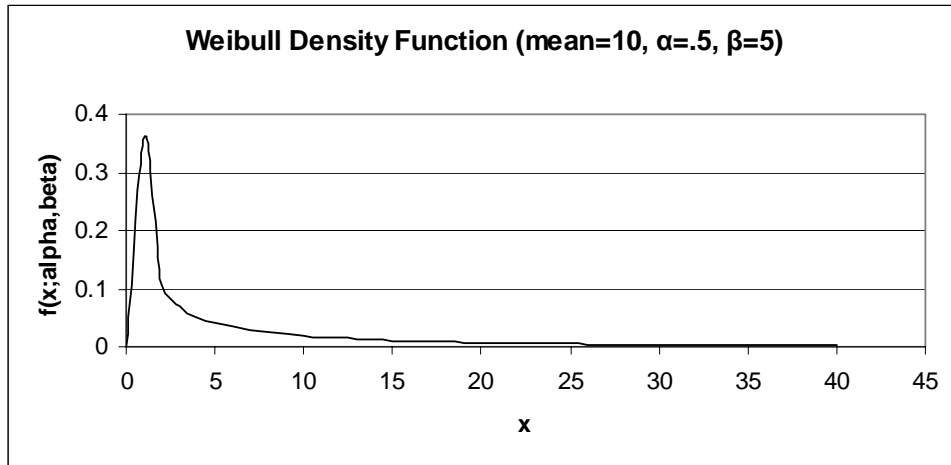
As shown in Figures 6 and 7 the CBM+ Process has a smaller mean number of system aborts and mean repair time than the Legacy Process until the probability of successful discovery of a DS during a downtime for the CBM+ sensor is degraded to approximately 12-15%. This corresponds roughly with the average of $P_L(h_n)$ ($n=1,2,\dots,1,250$) where h_n is the MMH for the Legacy inspection after mission n that is determined using the methodology in Chapter 4; the baseline $P_L(h)$ is determined using the sum of the daily, preflight, and postflight inspection MMH requirements. Since the baseline MMH is the most common MMH requirement, the baseline $P_L(h)$ is approximately equal to the average of $P_L(h)$ s. Abort times depend upon the α_W and β_W Weibull distribution parameters selected for M_A as described in Chapter 4. In the examples listed above the mean value selected for M_A 's Weibull distribution was 10 with shape parameter $\alpha_W=1.5$ and scale $\beta_W=11.07732168$. This means that on average it requires 2.5 missions for an engine's diagnostic symptom to become a mission abort

situation; the variance of the time until mission abort is 46.8059. This value was selected as a placeholder and does not indicate an actual estimation of engine abort occurrences. However, it does serve to illustrate a generic abort behavior as P_C is varied as seen in the previous two figures.

B. EXAMINING MISSION ABORT TIME VARIANCES

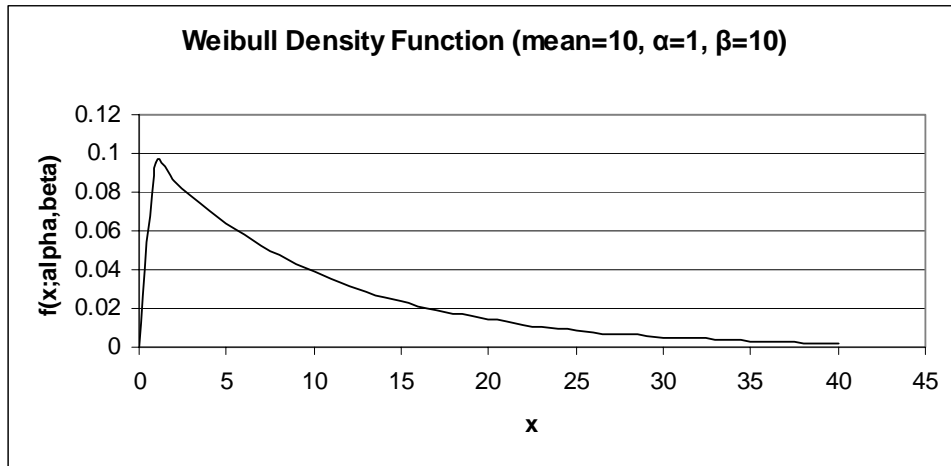
In this section we explore the effect the variance of the time from when a DS is generated until it causes mission abort has on the mean number of mission aborts. The mean time from when a DS is generated until it causes a mission abort is constant for all cases studied in this section. The parameters of the Weibull distribution are varied to obtain different variances. In this section the parameters of the beta distribution used to generate P_C for each DS are $\alpha_B=25$ and $\beta_B=.25$ giving an expected value of P_C equal to 0.99. The density functions of 3 different Weibull distributions are displayed in Figures 8, 9, and 10:

Figure 8. CASE #1 Weibull Density Function (mean=10, $\alpha_W=.5$, $\beta_W=5$)



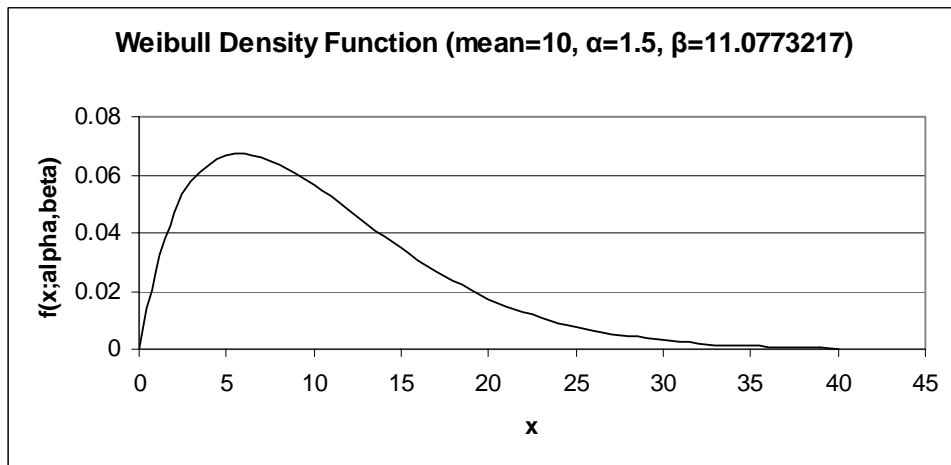
The Weibull distribution whose density function is displayed in Figure 8 has expected value equal to 10 and variance equal to 500.

Figure 9. CASE #2 Weibull Density Function (mean=10, $\alpha_W=1$, $\beta_W=10$)



The Weibull distribution whose density function is displayed in Figure 9 has expected value equal to 10 and variance equal to 100..

Figure 10. CASE #3 Weibull Density Function (mean=10, $\alpha_W=1.5$, $\beta_W=11.08$)



The Weibull distribution whose density function is displayed in Figure 10 has expected value equal to 10 and variance equal to 46.09.

The results of simulations of the two processes utilizing the three different cases of the Weibull distribution of the time from DS generation until it causes mission abort

with the mean P_C equal to 0.99 appear below. Summary statistics of the simulation output appearing in Appendix E indicate very small standard errors for the estimates of the fraction of DSs that cause mission abort. The fraction of DSs that cause mission aborts is defined as the number of DSs that actually cause a mission abort divided by the total number of DSs that occurred during 1,250 missions. This divisor is the sum of the DSs that caused mission aborts and DSs that did not cause mission aborts.

CASE #1 (Weibull with mean equal to 10, variance equal to 500, $\alpha_W=0.5$; $\beta_W=5$)

The fraction of DSs that causes a mission abort in the Legacy process is 0.64; the fraction of DSs that causes a mission abort is 0.37 in the CBM+ process. Recall that if more than one DS can cause a mission to abort, the mission is only aborted once. This means that given these conditions under the Legacy process a DS will result in a mission abort 64% of the time, whereas, under the CBM+ process a DS will result in a mission abort on 37% of the time.

CASE #2 (Weibull with mean equal to 10, variance equal to 100, $\alpha_W=1$; $\beta_W=10$)

The fraction of DSs that causes a mission abort in the Legacy process is 0.47; the fraction of DSs that causes a mission abort is 0.10 in the CBM+ process. Recall that if more than one DS can cause a mission to abort, the mission is only aborted once. This means that given these conditions under the Legacy process a DS will result in a mission abort 47% of the time, whereas, under the CBM+ process a DS will result in a mission abort on 10% of the time.

CASE #3 (Weibull with mean equal to 10, variance equal to 46.09, $\alpha_W=1.5$; $\beta_W=11.08$)

The fraction of DSs that causes a mission abort in the Legacy process is 0.40; the fraction of DSs that causes mission abort is 0.03 in the CBM+ process. Recall that if more than one DS can cause a mission to abort, the mission is only aborted once. This means that given these conditions under the Legacy process a DS will result in a mission abort 40% of the time, whereas, under the CBM+ process a DS will result in a mission abort on 3% of the time.

Thus the number of mission aborts depends on more than just the mean time from when a DS is generated until it causes mission abort. The variance associated with the mission abort arrival time can be equally influential. The CBM+ Process which monitors every mission with a high mean probability P_C of discovering DSs is most effective in preventing mission aborts in all cases but does best when the variance of the time from when a DS is generated until it causes mission abort is small.

C. EXAMINING MISSION ABORT TIME VARIANCES WITH DEGRADED P_C

In this section, the mean probability an existing DS is discovered during a downtime (P_C) is degraded from the value of 0.99 ($\alpha_B=25, \beta_B=.25$) to the smaller values of 0.50 ($\alpha_B=25, \beta_B=25$) and 0.20 ($\alpha_B=25, \beta_B=100$) in order to study the effect of the variance of the time from when a DS is generated until it causes a mission abort with a less effective sensor. The statistical standard errors of the summary statistics of the simulation output are displayed in Appendix E. The results for the Legacy Process remain as stated above since a varying P_C does not affect the Legacy Process. For all cases the Weibull parameters of the time until an undiscovered DS causes a mission abort $\alpha_W=1.5$ and $\beta_W=11.08$ are held constant.

CASE #1 (Weibull with mean equal to 10, variance equal to 500, $\alpha_W=0.5; \beta_W=5$)

This case possesses the largest variance and results in the probability an arriving DS will cause a mission abort for the CBM+ process equal to 0.45 ($P_C=0.50$) / 0.57 ($P_C=0.20$) of the time. This means that given a P_C of 0.50 that a DS will result in a mission abort 45% of the time. Given a P_C of 0.20, a DS will result in a mission abort 57% of the time.

CASE #2 (Weibull with mean equal to 10, variance equal to 100, $\alpha_W=1; \beta_W=10$)

This case possesses the middle variance and results in the probability an arriving DS will cause a mission abort for the CBM+ process equal to 0.17 ($P_C=0.50$) / 0.35 ($P_C=0.20$) of the time. This means that given a P_C of 0.50 that a DS will result in a mission abort 17% of the time. Given a P_C of 0.20, a DS will result in a mission abort 35% of the time.

CASE #3 (Weibull with mean equal to 10, variance equal to 46.09, $\alpha_w=1.5$; $\beta_w=11.08$)

This case possesses the smallest variance and results in the probability an arriving DS will cause a mission abort for the CBM+ process equal to 0.09 ($P_C=0.50$) / 0.25 ($P_C=0.20$) of the time. This means that given a P_C of 0.50 that a DS will result in a mission abort 9% of the time. Given a P_C of 0.20, a DS will result in a mission abort 25% of the time.

These results of examining P_C at both 0.50 and 0.20 are consistent with the conclusions drawn from examining mission abort arrival time variance when P_C is 0.99. Furthermore, it is concluded that even a very poor performing sensor (i.e. $P_C=0.20$) when compared against the Legacy process reduces the percentage of diagnostic symptoms that can result in mission aborts by an average of 10% regardless of the variance of the time from when a DS is generated until it can cause a mission abort. When the P_C is at 0.99 the CBM+ Process reduces the percentage of diagnostic symptoms that can result in a mission aborts by an average of 30%-35%. Legacy process performance data used in the comparisons above for these cases is displayed in Appendix E.

D. CBM+ FALSE POSITIVES

It is worthwhile to explore the consequences of the CBM+ sensor indicating a false positive. Since the Army currently uses only passive sensors whose measurements are downloaded at the conclusion of missions a false positive does not impact the mission during which it occurs. However, a false positive will require maintenance personnel to expend maintenance man-hours in order to determine that nothing is wrong with the component. The time required to inspect (repair) and correctly diagnose a diagnostic symptom as a false positive is the same as if it were an actual diagnostic symptom recognized immediately after the mission during which it arrived. This time penalty is a random variable drawn from an exponential distribution with a mean of 3 hours. False positives are assumed to occur according to a Poisson process independent of the other processes. Table 12 displays the mean number of false positive arrivals and their associated mean inspection (repair) times resulting from a simulation with 1,000

replications. The parameters of the simulation are: $\alpha_B=25$, $\beta_B=0.25$ ($P_C=0.99$); $\alpha_W=1.5$, $\beta_W=11.08$ (mean time until mission abort is 10 missions). The total amount of repair expended on false positives that appear during an operational time t is a compound Poisson process.

$$E[\text{total repair time}] = E[\text{number of false positives}] \times E[\text{repair time per false positive}]$$

An expanded version of Table 12 appears in Appendix E annotating standard errors.

Table 12. Simulation Results for mean number of False Positive Arrivals and mean Inspection (Repair) Time resulting from False Positives for 1,250 missions

| False Positive Rate | CBM+ PROCESS (NUMBER OF FALSE POSITIVE ARRIVALS) | | |
|---------------------|--|-------|----------------|
| 0.9999 | Σ FP | Mean: | 1238.57 |
| 0.90 | Σ FP | Mean: | 1115.29 |
| 0.80 | Σ FP | Mean: | 990.51 |
| 0.70 | Σ FP | Mean: | 866.70 |
| 0.60 | Σ FP | Mean: | 743.41 |
| 0.50 | Σ FP | Mean: | 620.23 |
| 0.40 | Σ FP | Mean: | 495.29 |
| 0.30 | Σ FP | Mean: | 372.07 |
| 0.20 | Σ FP | Mean: | 247.05 |
| 0.10 | Σ FP | Mean: | 124.34 |
| 0.0001 | Σ FP | Mean: | 0.14 |
| False Positive Rate | CBM+ PROCESS (REPAIR TIME INCURRED DUE TO FALSE POSITIVE ARRIVALS) | | |
| 0.9999 | Σ FP Time | Mean: | 3717.41 |
| 0.90 | Σ FP Time | Mean: | 3343.55 |
| 0.80 | Σ FP Time | Mean: | 2969.66 |
| 0.70 | Σ FP Time | Mean: | 2598.47 |
| 0.60 | Σ FP Time | Mean: | 2228.17 |
| 0.50 | Σ FP Time | Mean: | 1861.03 |
| 0.40 | Σ FP Time | Mean: | 1490.28 |
| 0.30 | Σ FP Time | Mean: | 1118.76 |
| 0.20 | Σ FP Time | Mean: | 741.94 |
| 0.10 | Σ FP Time | Mean: | 371.62 |
| 0.0001 | Σ FP Time | Mean: | 0.42 |

Displayed in Table 13 are the analytical results for the number of false positive arrivals and the resulting inspection (repair) time for 1,250 missions.

Table 13. Analytical Results for mean number of False Positive Arrivals and mean Inspection (Repair) Time resulting from False Positives for 1,250 missions

| False Positive Rate | CBM+ PROCESS (NUMBER OF FALSE POSITIVE ARRIVALS) | | |
|---------------------|--|-------|----------------|
| 0.9999 | $\sum FP$ | Mean: | 1249.88 |
| 0.90 | $\sum FP$ | Mean: | 1125.00 |
| 0.80 | $\sum FP$ | Mean: | 1000.00 |
| 0.70 | $\sum FP$ | Mean: | 875.00 |
| 0.60 | $\sum FP$ | Mean: | 750.00 |
| 0.50 | $\sum FP$ | Mean: | 625.00 |
| 0.40 | $\sum FP$ | Mean: | 500.00 |
| 0.30 | $\sum FP$ | Mean: | 375.00 |
| 0.20 | $\sum FP$ | Mean: | 250.00 |
| 0.10 | $\sum FP$ | Mean: | 125.00 |
| 0.0001 | $\sum FP$ | Mean: | 0.13 |
| False Positive Rate | CBM+ PROCESS (REPAIR TIME INCURRED DUE TO FALSE POSITIVE ARRIVALS) | | |
| 0.9999 | $\sum FP$ Time | Mean: | 3749.63 |
| 0.90 | $\sum FP$ Time | Mean: | 3375.00 |
| 0.80 | $\sum FP$ Time | Mean: | 3000.00 |
| 0.70 | $\sum FP$ Time | Mean: | 2625.00 |
| 0.60 | $\sum FP$ Time | Mean: | 2250.00 |
| 0.50 | $\sum FP$ Time | Mean: | 1875.00 |
| 0.40 | $\sum FP$ Time | Mean: | 1500.00 |
| 0.30 | $\sum FP$ Time | Mean: | 1125.00 |
| 0.20 | $\sum FP$ Time | Mean: | 750.00 |
| 0.10 | $\sum FP$ Time | Mean: | 375.00 |
| 0.0001 | $\sum FP$ Time | Mean: | 0.38 |

As expected the simulation results closely match the analytical results and produce a linear relationship as the false positive rate is varied from 0.9999 (false positive arriving every mission) to 0.0001 (false positives very rarely occurring).

Assuming that the Legacy process does not produce a false positive of its own it is useful to note that the Legacy process incurs approximately 75 hours in repair time every 1,250 missions. The Legacy process expected repair time includes all repair times including repair time resulting from mission aborts. Table 14 displays the mean CBM+ Process total repair time (total repair time = diagnostic symptom repair time + false

positive repair time) while varying the false positive rate from 0.10 to 0.0001. The mean time until mission abort is 10 missions ($\alpha_W=1.5$, $\beta_W=11.08$). An expanded table including standard errors is displayed in Appendix E.

Table 14. CBM+ Process mean Total Repair Time (including False Positive Repair Time) for 1,250 missions with $\alpha_B=25$, $\beta_B=.25$

| False Positive Rate | CBM+ PROCESS (TOTAL REPAIR TIME=DS REPAIR TIME+FALSE POSITIVE REPAIR TIME) | | |
|---------------------|---|-------|---------------|
| 0.10 | $\sum R + \sum FP$ Time | Mean: | 406.13 |
| 0.09 | $\sum R + \sum FP$ Time | Mean: | 369.59 |
| 0.08 | $\sum R + \sum FP$ Time | Mean: | 330.84 |
| 0.07 | $\sum R + \sum FP$ Time | Mean: | 291.50 |
| 0.06 | $\sum R + \sum FP$ Time | Mean: | 257.54 |
| 0.05 | $\sum R + \sum FP$ Time | Mean: | 221.93 |
| 0.04 | $\sum R + \sum FP$ Time | Mean: | 185.08 |
| 0.03 | $\sum R + \sum FP$ Time | Mean: | 146.10 |
| 0.02 | $\sum R + \sum FP$ Time | Mean: | 108.97 |
| 0.01 | $\sum R + \sum FP$ Time | Mean: | 71.91 |
| 0.0001 | $\sum R + \sum FP$ Time | Mean: | 36.06 |

Figure 11 is a graphical display of the total mean repair time of the Legacy and CBM+ Process as the false positive rate is varied from .05 to .0001.

Figure 11. Mean Total Repair Time for 1,250 Missions while varying the False Positive rate from .05 to .0001

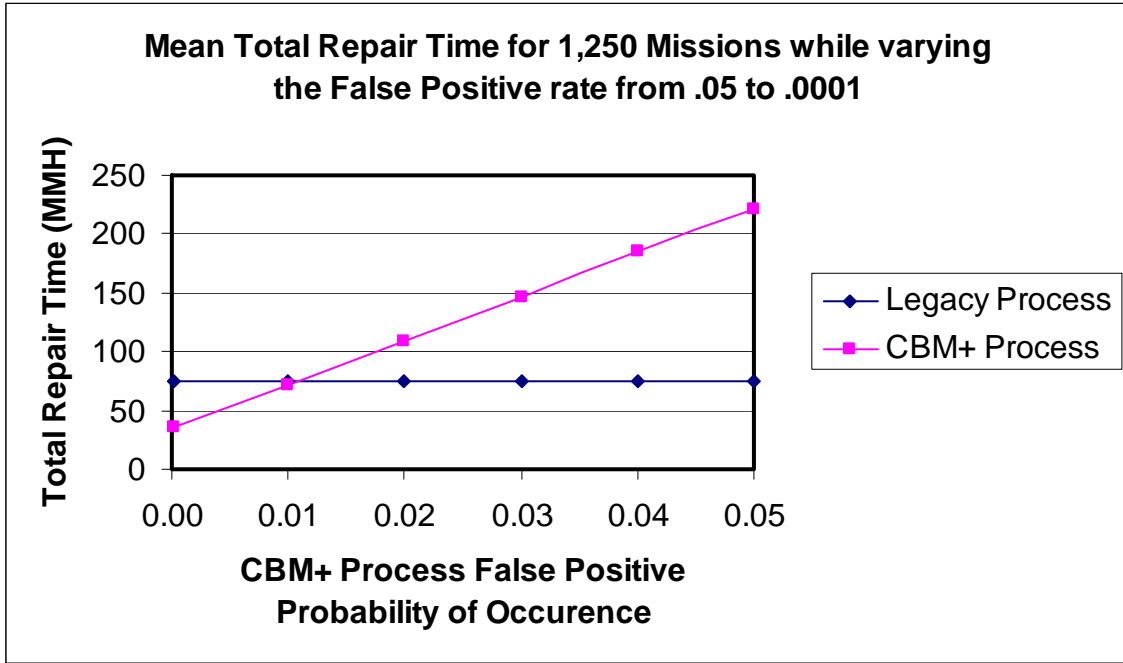


Figure 11 illustrates the importance of limiting the number of false positives that the CBM+ sensor incurs. This simulation was run with a mean probability of DS discovery during a downtime equal to $P_C=0.99$ (a highly accurate sensor) yet when false positive rates begin to increase any advantage in repair time provided by the sensor is quickly lost; the parameters of the beta distribution for P_C are $\alpha_B=25$ and $\beta_B=.25$. The parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$ (mean time until mission abort is 10 missions).

E. LOGISTICAL IMPLICATIONS OF VARYING P_C

It is possible to utilize this simulation to gain insights into the logistical implications of utilizing the CBM+ Process versus the traditional Legacy Process. The following is a general description of the logistics process. An assumption made is that once a DS occurs that the time remaining until mission abort is known; this is very optimistic. Another assumption is that there is only mission per day and that a mission occurs every day. This differs from the current implementation of CBM+ ; once a

component shows degraded performance it is removed; the time until failure is not known. For the case of a mean time until a replacement component arrives of 3 days (assuming one mission for every day) the following process is used:

1. A DS is detected.
2. If remaining time until a mission abort is greater than or equal to the time to fly 3 missions the 3 missions will be flown. The following events occur:
 - a. A replacement component is ordered and arrives before there is a mission abort; there is no time with aircraft down waiting for the replacement part (T_{OH}). Since one mission is flown per day, the time until the replacement component arrives is three days. This assumes both the number of missions until mission abort is known and the time until the replacement component arrives is constant and known. This fixed time is an approximate of the prognostics capability of the CBM+ sensor and can be modified as further research is done in this area.
3. If the remaining time until a mission abort is less than the time to fly 3 missions, the aircraft will not fly until the failing component is replaced. A Bernoulli random variable is generated with probability of success P_{OH} (probability component is on hand):
 - a. If a replacement component is on hand, there is no aircraft downtime waiting for the replacement component.
 - b. If component is not on hand an exponential time with mean of 3 is generated to determine T_{OH} (time in days spent awaiting component).

The following charts illustrate two cases. The first case is when a component requires a mean of 3 days to arrive once ordered and the second case is when a component requires a mean of 10 days to arrive once ordered. Through examining these two situations conclusions can be drawn concerning the effect of a CBM+ sensor on the component ordering time requirements. When a DS is discovered, the number of future missions that can be flown before a mission abort is calculated. One mission is flown per day. Thus the number of additional missions that can be flown is compared to the mean number of days until a replacement component can arrive. If the number of missions that

can be flown without a mission abort is less than the mean number of days until a replacement component arrives, then an independent Bernoulli random variable is generated to determine if the replacement component is on hand. If the component is not immediately available then an Exponential distribution is used to determine the amount of time required for component arrival. These random numbers are independent for the Legacy and CBM+ processes. P_{OH} will be used to represent the probability that a replacement component is on hand at the location of the unit requiring the component; when a DS is discovered whether or not a replacement component is at the location is independent from DS to DS. There is no randomization of the probability a replacement component is available. The value of P_{OH} will be varied from .9999 to .0001 in order to compare the mean number of days awaiting replacement components for both the CBM+ system and the Legacy system. The number of missions is 1,250 and there are 1,000 replications. The parameters of the CBM+ process are $\alpha_B=25$ and $\beta_B=.25$. The parameters of the Weibull distribution are $\alpha_W=1.5$, $\beta_W=11.08$ (the mean time until mission abort is 10 missions). Upon the occurrence of a mission abort or if the DS is discovered but it is not at least 3 days before the mission abort were to occur (CASE #1) or ten days before the mission abort were to occur (CASE #2) then a Bernoulli random variable is generated to determine whether or not the component is on hand (P_{OH}) and if the component is not on hand then an exponential distribution with mean 3 days (CASE #1) or 10 days (CASE #2) is used to determine the number of days spent awaiting component (T_{OH}). Summary statistics of the simulation output appear in Appendix E. The standard errors of the mean number of days expended until a replacement component arrives are small and this information is located in Appendix E for all graphs listed in the remainder of Chapter 5.

1. 3 Day Mean Component Ordering Time

The first case examines three different P_C levels for the CBM+ Process. The first P_C level is .99. The mean number of days expended awaiting replacement components as the P_{OH} is varied from .9999 to .0001 are displayed in Figure 12. DSs causing mission aborts are included.

Figure 12. Mean Number of Days Expended Awaiting Replacement Components where $P_C=.99$ and Mean Time until replacement component arrives=3 days

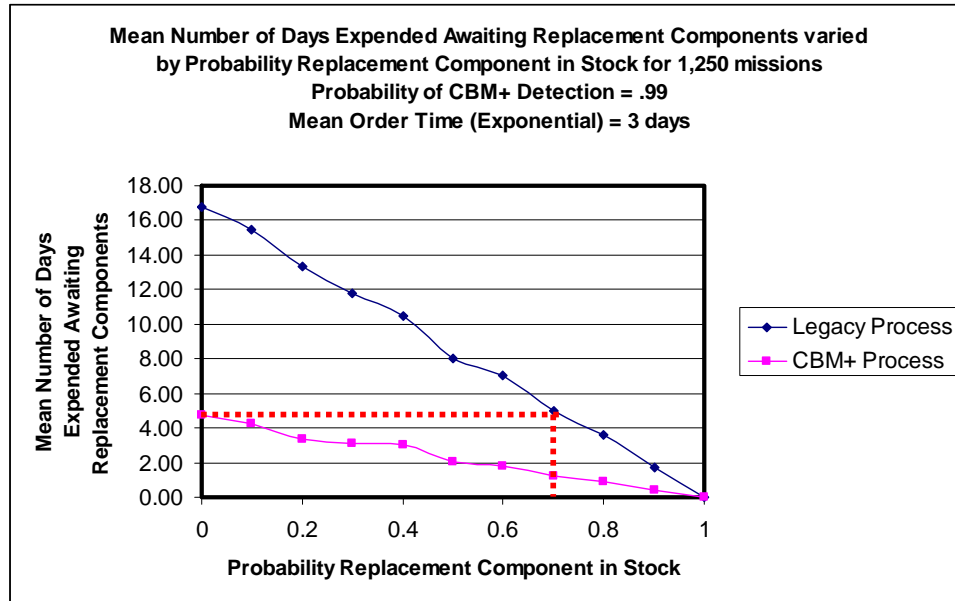


Figure 12 shows that if the remaining time until component failure is known perfectly then utilizing the CBM+ Process and having no the components on hand when P_C is .99 is equivalent to keeping approximately enough of the components on hand under the Legacy Process to have a replacement component immediately available 70% of the time. The reason the mean time expended waiting for replacement components is so different between the two processes is that since the CBM+ process discovers DSs so much earlier on average than the Legacy process, the CBM+ process is able to order the component before the component fails. The Legacy process does not have this advantage since it will either not detect until a mission abort or once a DS is discovered it is too late to order the component before the component fails. Figures 13 and 14 display the mean delay time until replacement components arrive, for P_C equal to 0.50 (respectively 0.20); if the remaining time until component failure is known perfectly, then the result for the case the CBM+ process has no components on hand is the same that for the Legacy process that has enough components at the location to replace 60% (respectively 30%) of the discovered DSs at their time of discovery.

Figure 13. Mean Number of Days Expended Awaiting Replacement Components where $P_C=.50$ and Mean Order Time=3 days

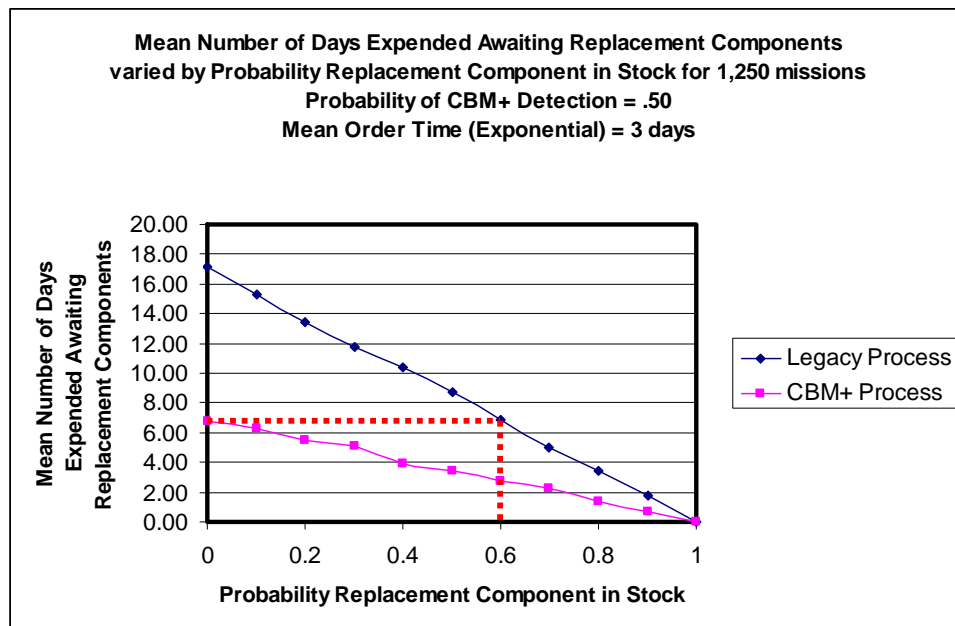
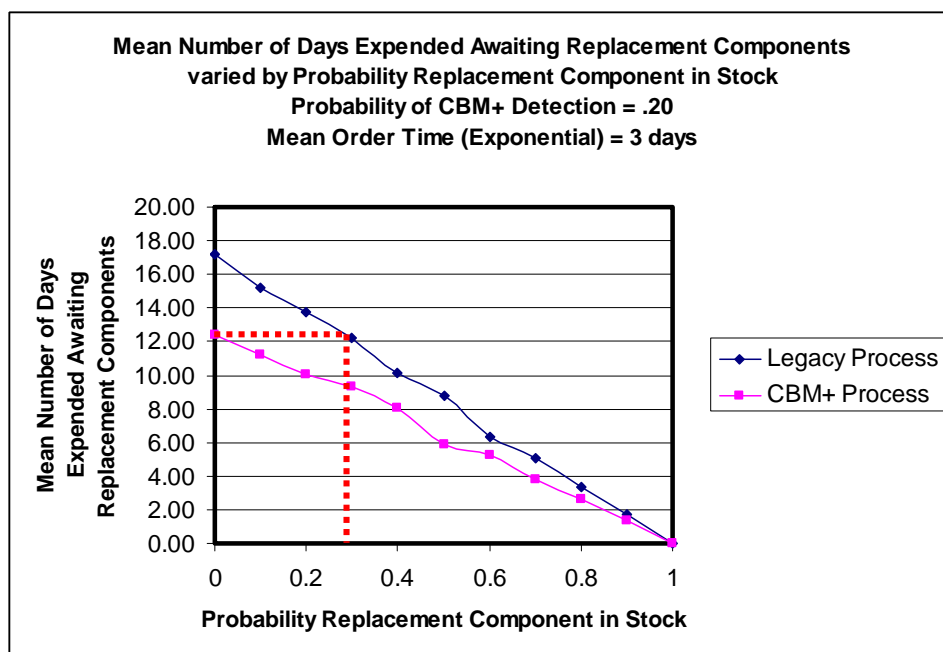


Figure 14. Mean Number of Days Expended Awaiting Replacement Components where $P_C=.20$ and Mean Order Time=3 days



2. 10 Day Mean Component Ordering Time

If the mean time of the exponential ordering time is increased to 10 days this will provide insight into the advantage of utilizing the CBM+ Process for a component that is not as readily available in the Army's logistical system.

A review of Figures 15, 16, and 17 show that if the remaining time to component failure is known when the P_C is .99 / .50 / .20 and no components are kept on hand that the equivalent mean wait time for ordered components is the same for keeping enough on hand under the Legacy Process to have this component available 30% / 20% / 10% of the time respectively. This suggests that if a component is to be chosen for entry in the CBM+ Process it is more beneficial to choose a component that can be shipped faster and not one that requires longer to arrive to the organization requiring the replacement component. The advantage that the CBM+ Process delivers is that it gives the maintainer advance warning that a component will fail in the near future. If the component can be ordered when a diagnostic symptom is recognized and sent to the organization requiring the component before the component causes mission abort then great savings in on hand stockage requirements can be realized; this assumes that the remaining time until mission abort can be predicted with accuracy. If the aircraft is grounded until replacement parts become available then the CBM process is comparable to the Legacy process. However, if the component requires a longer time to arrive then this advantage that the CBM+ Process possesses over the Legacy Process still exists but is diminished.

Figure 15. Mean Number of Days Expended Awaiting Replacement Components where $P_C=.99$ and Mean Order Time=10 days

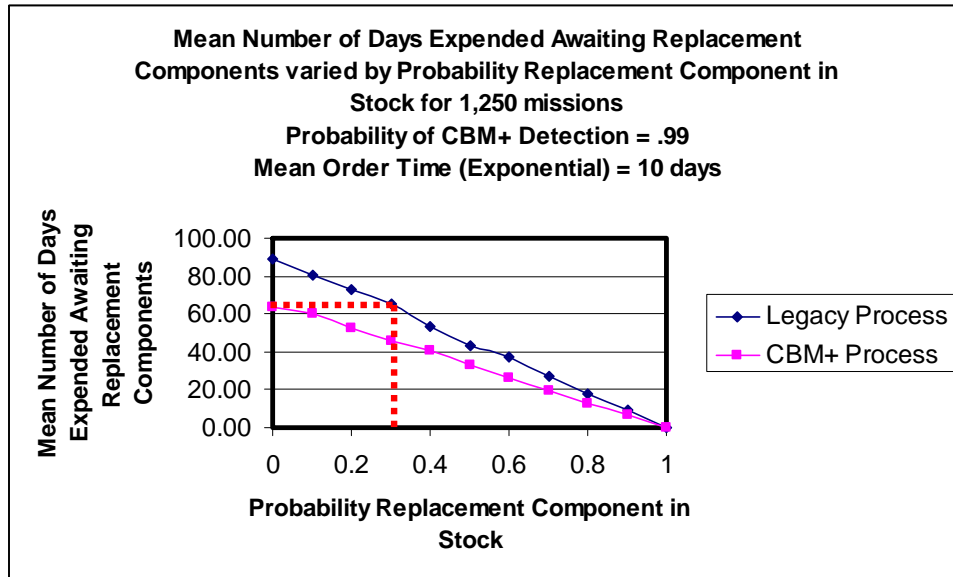


Figure 16. Mean Number of Days Expended Awaiting Replacement Components where $P_C=.50$ and Mean Order Time=10 days

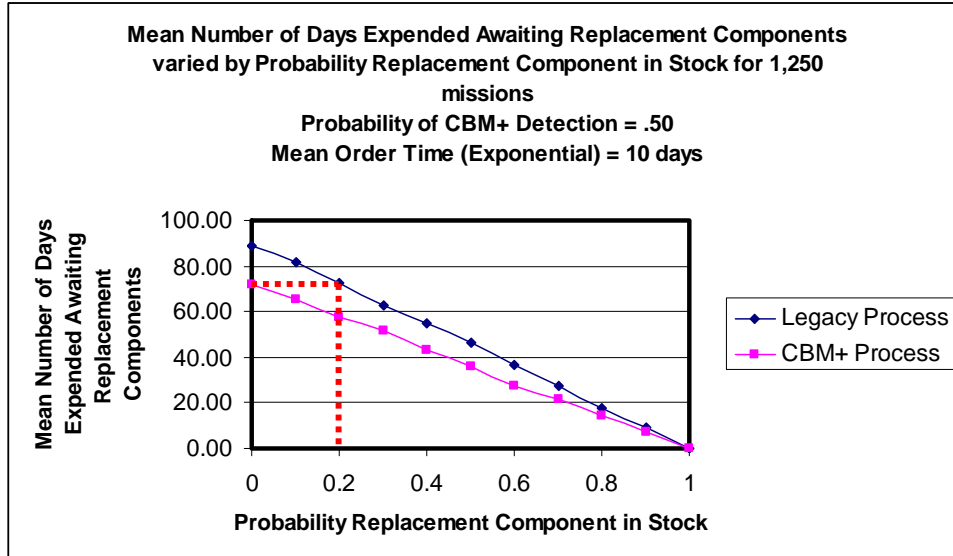
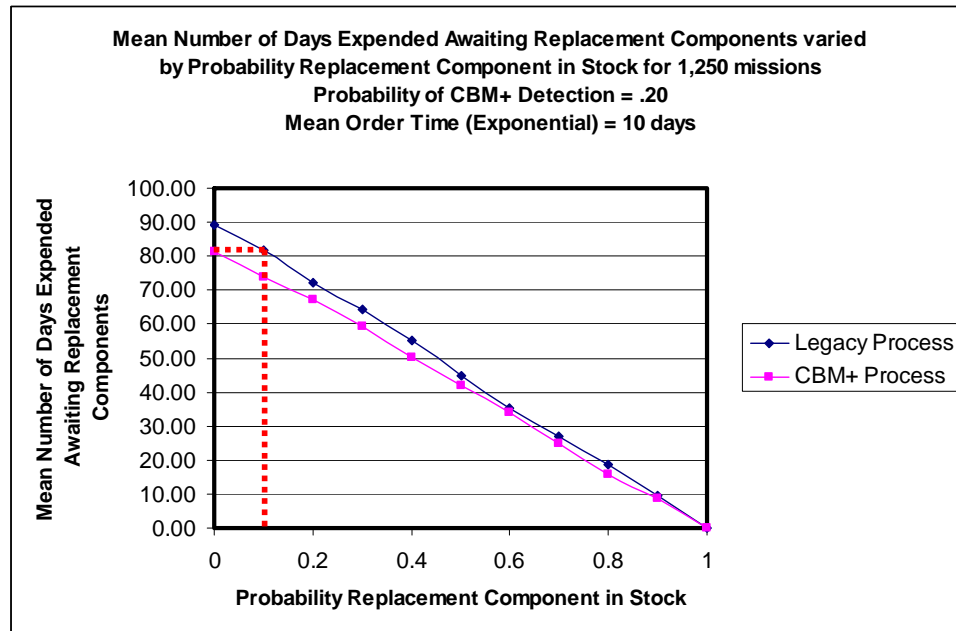


Figure 17. Mean Number of Days Expended Awaiting Replacement Components where $P_C=.20$ and Mean Order Time=10 days



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VI. RESULTS AND CONCLUSIONS

A. APPLICATIONS

A model of the Legacy maintenance/repair process and the CBM+ maintenance/repair process has been presented. The model assumes that prior to a component failure, a measurable diagnostic symptom (DS) appears. Once a DS is generated, it remains measurable and can be detected by a CBM+ sensor or by physical inspection (Legacy process). The model output includes the number of missions that are aborted and the repair time incurred by component failures and false positives. By comparing two or more different components it is possible to determine which component will produce more favorable results in terms of mission abort rates and repair time expenditures by introducing it into the CBM+ process. Furthermore, patterns and behaviors can be observed as conditions vary thereby providing insight and information to be used by the decision-maker.

The following factors are influential to the successful introduction of a component in a CBM+ program:

1. Since the CBM+ sensor is continually monitoring a component, the sensor doesn't have to have an extremely high level of probability of detection of diagnostic symptoms; this result assumes that the probability of detection of a DS is independent from mission to mission. It also assumes that once a DS has occurred it remains detectable; that is measurable evidence of the DS is not intermittent. Simply by providing a level of detection for every mission that exceeds the baseline (the daily pre-flight and post-flight inspections) probability of detection provided by the Legacy Process the CBM+ Process will show a substantial increase in the maintainer's ability to recognize and mitigate impending mission aborts. However, this advantage will decrease if the sensor produces false alarms.

2. When selecting a component for entry in the CBM+ Process more than just a comparison of the mean times between the arrival of a diagnostic symptom until development of a mission abort are required. The variance of the mean time until mission abort given that a diagnostic symptom has occurred is equally important. A

CBM+ sensor may be less effective if the time from when a DS is generated until it causes a mission abort has a high variance. This finding remains true for degraded levels of mean probability a DS is discovered, P_C . Data concerning the time from when a DS is generated until component failure would be very informative in judging whether to include a component in the CBM+ process.

3. Whereas a component's CBM+ sensor doesn't need an extremely high probability of detection that a DS has occurred, it is extremely important that false positives be kept to extremely low levels. Otherwise, the advantage of continual inspection using sensors begins to work against the CBM+ Process. If a component whose CBM+ sensor provides a fair number of false positives (i.e. 5% of the missions result in a false positive) the time spent by maintenance personnel confirming that the DS was in fact a false positive quickly overshadows any gains in actual repair times.

To reiterate some factors to consider when considering introducing a component to the CBM+ process from Chapter 3:

1. How often does the component fail during active flight hours?

It is preferable to introduce a component that fails often versus components that rarely fail.

2. What are the consequences of a component failing?

It is preferable to introduce a component that possesses severe consequences for failure versus a component that is inconsequential in its failure.

3. What is the difficulty level of the inspection that would be alleviated by CBM+?

If an inspection is extremely difficult and resource intensive to perform, it would be preferable to have this inspection replaced by CBM+ versus an inspection that is simple and easy to perform.

4. Is a CBM+ sensor feasible for a component?

If measurements cannot be taken to assess the degradation of the component before it fails, i.e. no useful DS, then that component would not be a good CBM+

candidate. Furthermore, the time from when the occurrence of measurable evidence of impending failure until failure should be long enough to detect the impending failure and take maintenance action.

5. What is the reliability of the CBM+ sensor, the difficulty of inspecting the CBM+ sensor, and the effect of the CBM+ sensor on performance of the component being monitored? Is there a CBM+ sensor currently developed for a component? What is the cost of the sensor?

B. RECOMMENDATIONS FOR FUTURE STUDY

Models for the following random variables are selected as placeholders. Collection and analysis of data are needed to provide more appropriate models.

1. M_A : (time from when a DS occurs until it causes a mission abort) A Weibull distribution with a mean of 10 hours was selected. The distributional form is conjectural. Experiments need to be designed and conducted to collect data concerning the time from when a DS is generated by a component until the DS causes the component to fail. It is also important to collect data on the time from when a DS is generated until the sensor detects the DS.

2. R_0 : (initial repair time) An Exponential distribution with a mean of 3 hours was selected. This provided the initial mean repair time incurred upon a DS discovery.

3. R_1 : (subsequent fixed repair time) A fixed value of 3 hours was chosen. This provided for an additional repair time if the DS was not discovered after the first mission in which it arrived. This value was only applied once. For example, R_1 was the same if the DS was discovered after the second mission it appeared or the tenth mission after it appeared.

4. A_0 : (initial repair time resulting from a mission abort) An Exponential distribution with a mean of 5 hours was selected. This provided mean repair time incurred upon a mission abort.

5. A_1 : (subsequent fixed repair time resulting from a mission abort) A fixed value of 5 hours was chosen. This provided for an additional repair time if the DS that caused

the mission abort was not discovered after the first mission in which it arrived. This value was only applied once. For example, A_1 was the same if the DS was discovered after the second mission it appeared or the tenth mission after it appeared.

It is also important to conduct a study of the reliability and maintainability of the CBM+ sensors. It is envisioned that CBM+ sensors will eliminate the need for scheduled inspection and maintenance. A sensor may be able to detect the occurrence of a DS; however, if the sensor experiences failure often and is difficult to inspect and maintain, the effectiveness of the sensor will be diminished. In addition it is important to study the ability of the logistics process to respond to the sensor measurements. If it takes a long time to analyze sensor measurements and/or obtain replacement components, then the attractiveness of introducing a component into CBM is lessened. The cost of the sensor also needs to be considered.

APPENDIX A. AH-64/UH-60 701C ENGINE DATA

| SN | EI_SN | MODEL | Date | REP_NU M | CE N | LIFE | TSN | F_TYPE | FCOD E | Failure | FAMILY |
|---------------|---------|-------------|----------------|-------------|---------|-------|----------|----------------|-----------|---|-------------|
| GEE76106 7 | 9126370 | MH-60K | 5/17/2001 | 1 | 0 | 944 | 944 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76106 7 | 8926194 | MH-60K | 2/19/2002 | 2 | 0 | 231 | 117 8 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76106 7 | 9426547 | MH-60L | 1/8/2003 | 3 | 0 | 246 | 142 6 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76106 7 | 9026285 | MH-60L | 3/9/2004 | 4 | 0 | 285 | 171 2 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76106 7 | 9026285 | MH-60L | 8/5/2005 | 4 | 0 | 372 | 208 5 | C1_REMOVA L | 374 | INTERNAL FAILURE | Assembly |
| GEE76115 8 | 9026295 | UH-60L | 10/11/200 1 | 1 | 0 | 1873 | 187 3 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76115 8 | 9226426 | UH-60L | 9/26/2002 | 2 | 0 | 256 | 212 9 | C1_REMOVA L | 374 | INTERNAL FAILURE | Assembly |
| GEE76115 8 | 8900227 | AH-64A | 3/15/2003 | 3 | 0 | 245 | 237 4 | C1_REMOVA L | 585 | SHEARED | Op/FOD |
| GEE76115 8 | 9626689 | UH-60L | 9/10/2003 | 4 | 1 | 1034 | 237 6 | INSTALLED | 799 | NO DEFECT- SERVICEABLE OUT OF ADJUSTMT, OUT OF TOLERA | NoDefect |
| GEE76125 9 | 9126329 | UH-60L | 2/14/2001 | 1 | 0 | 1573 | 157 3 | C1_REMOVA L | 790 | | Tol/Bal |
| GEE76125 9 | 8900235 | AH-64A | 3/11/2003 | 2 | 0 | 412 | 198 6 | C1_REMOVA L | 372 | METAL ON MAGNETIC PLUG | |
| GEE76125 9 | | UNKNOW N | 2/10/2004 | 3 | 0 | 249 | 223 5 | C3C2ACT | 20 | WORN EXCESSIVELY | Rem Unkn |
| GEE76125 9 | 9000482 | AH-64A | 9/15/2004 | 4 | 1 | 339.8 | 234 9 | INSTALLED | 799 | NO DEFECT- SERVICEABLE BEYOND SPECIFIED TOLERANCE | NoDefect |
| GEE76170 5 | 9705043 | AH-64D | 2/22/2002 | 1 | 0 | 1729 | 172 9 | C1_REMOVA L | 705 | | Tol/Bal |
| GEE76170 5 | | UNKNOW N | 11/29/200 3 | 2 | 0 | 254 | 198 8 | C3C2ACT | 181 | LOW COMPRESSION | Rem Unkn |
| GEE76170 5 | | UNKNOW N | 8/19/2004 | 3 | 0 | 97 | 208 5 | C3C2ACT | 855 | HEAT DAMAGE | Rem Unkn |
| GEE76170 5 | 5201 | AH-64D | 8/19/2004 | 4 | 1 | 305.8 | 208 5 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76173 5 | 9000294 | AH-64A | 12/11/200 1 | 1 | 0 | 1769 | 176 9 | C1_REMOVA L | 374 | INTERNAL FAILURE | Assembly |
| GEE76173 5 | 9000294 | AH-64A | 7/18/2003 | 2 | 0 | 393 | 216 3 | C1_REMOVA L | 329 | STARTING STALL | |
| GEE76173 5 | | UNKNOW N | 2/4/2005 | 3 | 0 | 165 | 233 0 | C3C2ACT | 230 | DIRTY | Rem Unkn |
| GEE76173 5 | 9926829 | UH-60L | 2/8/2005 | 4 | 1 | 106.5 | 233 0 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76174 5 | 9000306 | AH-64A | 10/24/200 2 | 1 | 0 | 1812 | 181 2 | C1_REMOVA L | 519 | SURGED | |
| GEE76174 5 | | UNKNOW N | 8/11/2003 | 2 | 0 | 106 | 192 0 | C3C2ACT | 537 | LOW POWER OR TORQUE | Rem Unkn |

| | | | | | | | | | | | |
|---------------|-------------|-------------|----------------|---|---|--------|----------|----------------|-----|--------------------------------------|-------------|
| GEE76174 5 | | UNKNOW N | 1/24/2004 | 3 | 0 | 125 | 204 5 | C3C2ACT | 230 | DIRTY | Rem Unkn |
| GEE76174 5 | 9326486 | UH-60L | 3/2/2004 | 4 | 0 | 5 | 205 0 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76174 5 | 9326525 | UH-60L | 2/1/2005 | 4 | 0 | 284 | 233 6 | C1_REMOVA L | 374 | INTERNAL FAILURE | Assembly |
| GEE76174 5 | 9626678 | UH-60L | 9/10/2005 | 4 | 1 | 136.5 | 234 0 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76181 6 | 9126373 | MH-60K | 9/6/2002 | 1 | 0 | 2055 | 205 5 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76181 6 | 9026293 | UH-60L | 5/22/2003 | 2 | 0 | 129 | 218 4 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76181 6 | 9126363 | MH-60L | 11/24/200 3 | 3 | 0 | 144 | 232 9 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76181 6 | 9126360 | MH-60L | 6/5/2004 | 4 | 0 | 61 | 239 0 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76181 6 | 8926184 | MH-60L | 5/9/2005 | 4 | 0 | 236 | 262 6 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76181 6 | 8926184 | MH-60L | 6/8/2005 | 4 | 1 | 118.7 | 262 6 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76205 5 | 9126379 | MH-60K | 4/22/2002 | 1 | 0 | 2027 | 202 7 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76205 5 | 9126379 | MH-60K | 3/24/2003 | 2 | 0 | 239 | 226 7 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76205 5 | | UNKNOW N | 9/17/2005 | 3 | 0 | 329 | 284 1 | C3C2ACT | 537 | LOW POWER OR TORQUE | Rem Unkn |
| GEE76205 5 | 305400 | AH-64D | 1/3/2006 | 4 | 1 | 2838.9 | 284 1 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76228 7 | | UNKNOW N | 1/8/2001 | 1 | 0 | 1379 | 137 9 | C3C2ACT | 537 | LOW POWER OR TORQUE | Rem Unkn |
| GEE76228 7 | 9826825 | UH-60L | 8/20/2002 | 2 | 0 | 487 | 186 6 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76228 7 | 8926182 | UH-60L | 9/10/2003 | 3 | 0 | 172 | 204 2 | C1_REMOVA L | 180 | CLOGGED | |
| GEE76228 7 | 9026294 | UH-60L | 5/12/2004 | 4 | 0 | 223 | 226 5 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76228 7 | UNKN@L 2 | UNKNOW N | 1/4/2005 | 4 | 1 | 250.6 | 226 7 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76238 5 | 9326503 | UH-60L | 9/25/2002 | 1 | 0 | 1549 | 154 9 | C1_REMOVA L | 290 | FAILS DIAGNOSTIC/AUTO MATIC TE | HeaterBk |
| GEE76238 5 | 9426583 | UH-60L | 2/2/2004 | 2 | 0 | 50 | 159 9 | C1_REMOVA L | 70 | BROKEN | Broken |
| GEE76238 5 | 9426558 | UH-60L | 2/18/2005 | 3 | 0 | 346 | 194 5 | C1_REMOVA L | 307 | OIL LEAK | |
| GEE76238 5 | 9426587 | UH-60L | 7/27/2005 | 4 | 1 | 283.1 | 194 5 | INSTALLED | 307 | OIL LEAK | |
| GEE76243 6 | | UNKNOW N | 2/16/2001 | 1 | 0 | 1413 | 141 3 | C3C2ACT | 381 | LEAKING (LIQUID) | Rem Unkn |
| GEE76243 6 | | UNKNOW N | 10/11/200 3 | 2 | 0 | 514 | 192 7 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76243 6 | 305368 | AH-64D | 5/5/2005 | 3 | 0 | 102 | 206 7 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |

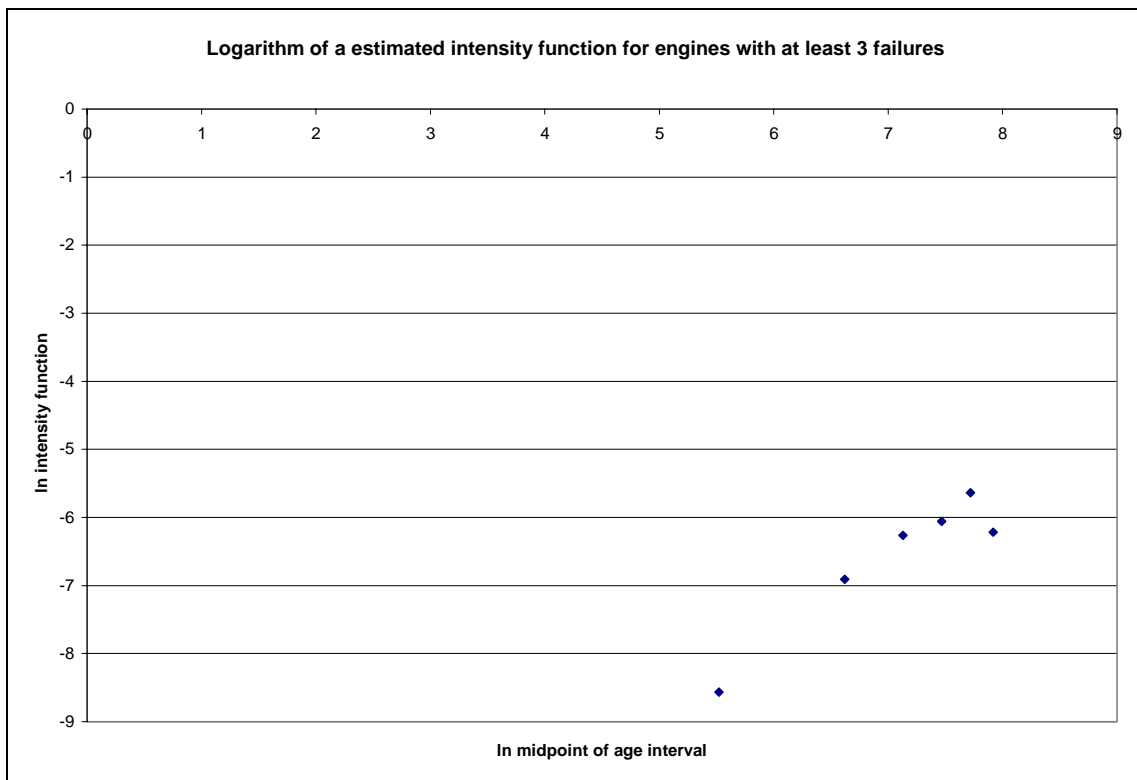
| | | | | | | | | | | | |
|---------------|---------|-------------|----------------|---|---|------------|----------|----------------|-----|----------------------------------|-------------|
| GEE76243 6 | 205319 | AH-64D | 5/17/2005 | 4 | 1 | 241.2 | 206 7 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76244 0 | | UNKNOW N | 11/13/200 2 | 1 | 0 | 1488 | 148 8 | C3C2ACT | 537 | LOW POWER OR TORQUE | Rem Unkn |
| GEE76244 0 | 9226452 | UH-60L | 10/28/200 3 | 2 | 0 | 236 | 172 4 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76244 0 | 205295 | AH-64D | 11/17/200 4 | 3 | 0 | 251 | 197 5 | C1_REMOVA L | 374 | INTERNAL FAILURE | Assembly |
| GEE76244 0 | 9026250 | UH-60L | 11/28/200 5 | 4 | 1 | 23.9 | 197 8 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76252 3 | | UNKNOW N | 12/9/2002 | 1 | 0 | 1432 | 143 2 | C3C2ACT | 537 | LOW POWER OR TORQUE | Rem Unkn |
| GEE76252 3 | 9226452 | UH-60L | 6/6/2003 | 2 | 0 | 124 | 155 6 | C1_REMOVA L | 181 | LOW COMPRESSION | Debond |
| GEE76252 3 | 9626685 | UH-60L | 11/3/2004 | 3 | 0 | 352 | 192 1 | C1_REMOVA L | 381 | LEAKING (LIQUID) | AirLeak |
| GEE76252 3 | 9905114 | AH-64D | 9/15/2005 | 4 | 1 | 209.6 | 192 6 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76260 6 | 9426561 | UH-60L | 9/9/2003 | 1 | 0 | 2115 | 211 5 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76260 6 | 9426561 | UH-60L | 12/9/2003 | 2 | 0 | 14 | 212 9 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76260 6 | 9526597 | UH-60L | 3/1/2004 | 3 | 0 | 5 | 213 4 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76260 6 | 9426552 | UH-60L | 7/13/2004 | 4 | 1 | 576.8 | 213 6 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76299 3 | | UNKNOW N | 11/22/200 2 | 1 | 0 | 1082 | 108 2 | C3C2ACT | 537 | LOW POWER OR TORQUE | Rem Unkn |
| GEE76299 3 | | UNKNOW N | 10/23/200 3 | 2 | 0 | 149 | 123 0 | C3C2ACT | 181 | LOW COMPRESSION | Rem Unkn |
| GEE76299 3 | 9705046 | AH-64D | 4/30/2004 | 3 | 0 | 135 | 136 5 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76299 3 | 9705046 | AH-64D | 5/20/2004 | 4 | 1 | 1159. 6 | 148 6 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76302 8 | 9026269 | UH-60L | 2/2/2002 | 1 | 0 | 956 | 956 | C1_REMOVA L | 307 | OIL LEAK | |
| GEE76302 8 | 9626674 | UH-60L | 10/26/200 4 | 2 | 0 | 140 | 109 6 | C1_REMOVA L | 315 | RPM FLUCTUATION/INC ORRECT | |
| GEE76302 8 | 9626682 | UH-60L | 12/27/200 4 | 3 | 0 | 0 | 109 6 | C1_REMOVA L | 381 | LEAKING (LIQUID) | AirLeak |
| GEE76302 8 | 9626676 | UH-60L | 9/23/2005 | 4 | 0 | 374 | 147 0 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76310 2 | 9705041 | AH-64D | 6/29/2005 | 1 | 0 | 0 | 0 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76310 2 | 9705041 | AH-64D | 6/29/2005 | 2 | 0 | 1970 | 197 0 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |
| GEE76310 2 | | UNKNOW N | 9/11/2005 | 3 | 0 | 2 | 197 2 | C3C2ACT | 537 | LOW POWER OR TORQUE | Rem Unkn |
| GEE76310 2 | 305347 | AH-64D | 12/31/200 5 | 4 | 1 | 0 | 197 2 | INSTALLED | 799 | NO DEFECT- SERVICEABLE | NoDefect |
| GEE76326 0 | 9826805 | UH-60L | 2/23/2001 | 1 | 0 | 696 | 696 | C1_REMOVA L | 374 | INTERNAL FAILURE | Assembly |
| GEE76326 0 | 9826805 | UH-60L | 2/21/2002 | 2 | 0 | 271 | 967 | C1_REMOVA L | 537 | LOW POWER OR TORQUE | Other |

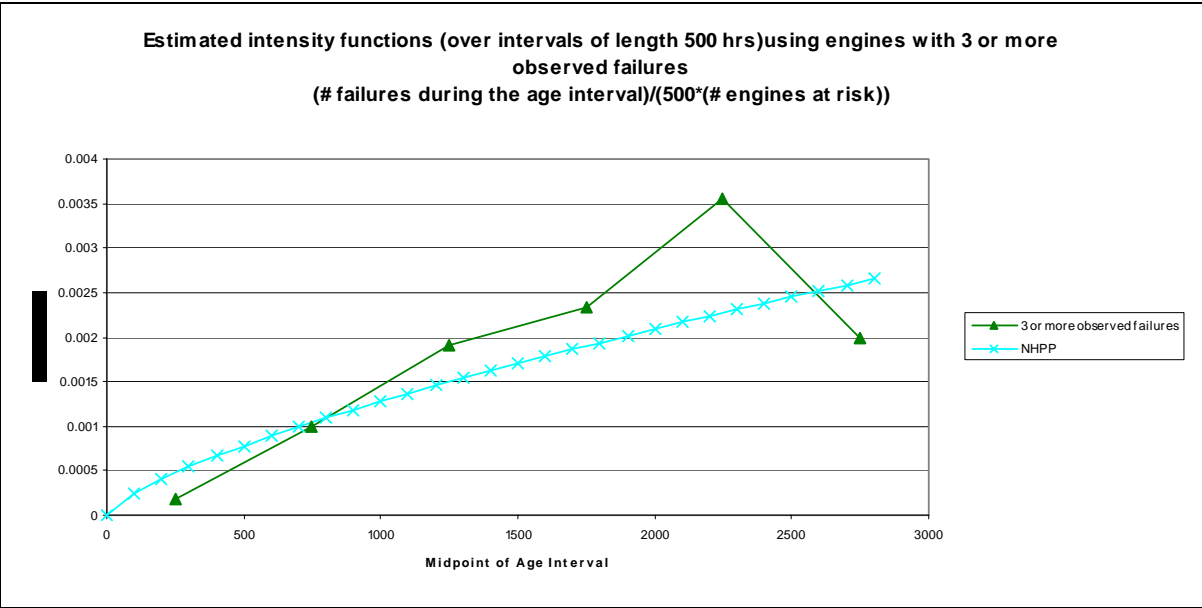
| | | | | | | | | | | | |
|---------------|---------|--------|------------|---|---|-------|----------|------------|-----|---------------------------------|----------|
| GEE76326 0 | 9826805 | UH-60L | 6/16/2003 | 3 | 0 | 499 | 146 9 | C1_REMOVAL | 855 | HEAT DAMAGE | HeaterBk |
| GEE76326 0 | 9426587 | UH-60L | 10/20/2003 | 4 | 0 | 171 | 164 0 | C1_REMOVAL | 537 | LOW POWER OR TORQUE | Other |
| GEE76326 0 | 9605015 | AH-64D | 1/10/2005 | 4 | 1 | 573.5 | 164 3 | INSTALLED | 799 | NO DEFECT-SERVICEABLE | NoDefect |
| GEE76330 1 | 9826823 | UH-60L | 5/8/2003 | 1 | 0 | 983 | 983 | C1_REMOVAL | 290 | FAILS DIAGNOSTIC/AUTOMATIC TEST | HeaterBk |
| GEE76330 1 | 9826805 | UH-60L | 8/30/2003 | 2 | 0 | 163 | 114 6 | C1_REMOVAL | 20 | WORN EXCESSIVELY | Erosion |
| GEE76330 1 | 9826826 | UH-60L | 1/15/2004 | 3 | 0 | 134 | 128 0 | C1_REMOVAL | 374 | INTERNAL FAILURE | Assembly |
| GEE76330 1 | 9026294 | UH-60L | 5/27/2004 | 4 | 0 | 35 | 131 8 | C1_REMOVAL | 105 | LOOSE BOLTS, NUTS, SCREWS | Assembly |
| GEE76330 1 | 8926182 | UH-60L | 12/30/2004 | 4 | 0 | 58 | 137 6 | C1_REMOVAL | 381 | LEAKING (LIQUID) | AirLeak |
| GEE76330 1 | 9526603 | UH-60L | 4/19/2005 | 4 | 1 | 115 | 137 8 | INSTALLED | 799 | NO DEFECT-SERVICEABLE | NoDefect |
| GEE76338 3 | 9426558 | UH-60L | 3/8/2003 | 1 | 0 | 742 | 742 | C1_REMOVAL | 537 | LOW POWER OR TORQUE | Other |
| GEE76338 3 | 9926830 | UH-60L | 8/25/2004 | 2 | 0 | 513 | 125 5 | C1_REMOVAL | 513 | STALLS, COMPRESSOR | |
| GEE76338 3 | 9226448 | UH-60L | 11/16/2004 | 3 | 0 | 1 | 125 6 | C1_REMOVAL | 513 | STALLS, COMPRESSOR | |
| GEE76338 3 | 9126332 | UH-60L | 8/10/2005 | 4 | 1 | 104.2 | 125 9 | INSTALLED | 799 | NO DEFECT-SERVICEABLE | NoDefect |
| GEE76340 1 | 9426575 | UH-60L | 12/1/2001 | 1 | 0 | 422 | 422 | C1_REMOVAL | 381 | LEAKING (LIQUID) | AirLeak |
| GEE76340 1 | 9426569 | UH-60L | 3/27/2003 | 2 | 0 | 266 | 689 | C1_REMOVAL | 381 | LEAKING (LIQUID) | AirLeak |
| GEE76340 1 | 9426568 | UH-60L | 9/11/2003 | 3 | 0 | 3 | 692 | C1_REMOVAL | 381 | LEAKING (LIQUID) | AirLeak |
| GEE76340 1 | 9426577 | UH-60L | 11/7/2003 | 4 | 0 | 4 | 696 | C1_REMOVAL | 307 | OIL LEAK | |
| GEE76340 1 | 9526649 | UH-60L | 7/14/2005 | 4 | 0 | 108 | 806 | C1_REMOVAL | 513 | STALLS, COMPRESSOR | |

APPENDIX B. ESTIMATED INTENSITY FUNCTIONS USING ENGINES WITH 3 OR MORE OBSERVED FAILURES

The table and figure in this Appendix are taken from Professor Patricia A. Jacobs' "A Nonhomogeneous Poisson process model (NHPP) for engine data" written 27 March 2006.

| Estimated intensity function for engines with at least 3 recorded failures | | | |
|--|------|---|------------------------|
| Age interval | | Number of failures (number of engines) | Estimated failure rate |
| 0 | 500 | 2 (21) | 0.00019 |
| 501 | 1000 | 10 (20) | 0.001 |
| 1001 | 1500 | 19 (20) | 0.0019 |
| 1501 | 2000 | 21 (18) | 0.0023 |
| 2001 | 2500 | 16 (9) | 0.0036 |
| 2501 | 3000 | 2 (2) | 0.002 |





APPENDIX C. ESTIMATION OF γ AND δ

Let $\{N(t); t \geq 0\}$ be a NHPP with mean value function $\Lambda(t) = \gamma t^\delta$ having intensity function $\lambda(t) = \gamma \delta t^{\delta-1}$. There are K systems. The k th system has n_k observed times of failure; the i th failure occurs at time t_{ik} . The k th system is observed for a time T_k . Maximum likelihood can be used to estimate the parameters.

The likelihood function is

$$L = \prod_{k=1}^L \prod_{i=1}^{n_k} \lambda(t_{ik}) \exp\{-\Lambda(T_k)\} \quad (\text{A1})$$

Taking logarithms results in the log likelihood

$$\ell(\gamma, \delta) = \ln(\gamma) \sum_{k=1}^K n_k + \ln(\delta) \sum_{k=1}^K n_k + (\delta - 1) \sum_{k=1}^K \sum_{i=1}^{n_k} t_{ik} - \gamma \sum_{k=1}^K T_k^\delta \quad (\text{A2})$$

Partial differentiation of the log-likelihood results in

$$\frac{\partial \ell(\gamma, \delta)}{\partial \gamma} = \frac{1}{\gamma} \sum_{k=1}^K n_k - \sum_{k=1}^K T_k^\delta \quad (\text{A3})$$

Setting the partial derivative equal to 0 and solving results in

$$\gamma = \frac{\sum_{k=1}^K n_k}{\sum_{k=1}^K T_k^\delta} \quad (\text{A4})$$

$$\begin{aligned}
\frac{\partial \ell(\gamma, \delta)}{\partial \delta} &= \frac{1}{\delta} \sum_{k=1}^K n_k + \sum_{k=1}^K \sum_{i=1}^{n_k} t_{ik} - \gamma \sum_{k=1}^K T_k^\delta \ln(T_k) \\
&= \frac{1}{\delta} \sum_{k=1}^K n_k + \sum_{k=1}^K \sum_{i=1}^{n_k} t_{ik} - \frac{\sum_{k=1}^K n_k}{\sum_{k=1}^K T_k^\delta} \sum_{k=1}^K T_k^\delta \ln(T_k)
\end{aligned} \tag{A5}$$

Setting the partial derivative equal to 0 results in an equation that can be solved numerically providing an estimate of δ and γ .

The second partial derivative of the log-likelihood result in

$$\frac{\partial^2 \ell}{\partial \delta \partial \gamma} = \sum_{k=1}^K T_k^\delta \ln(T_k) \tag{A6}$$

$$\frac{\partial^2 \ell}{\partial \gamma^2} = -\frac{1}{\gamma^2} \sum_{k=1}^K n_k \tag{A7}$$

$$\frac{\partial^2 \ell}{\partial \delta^2} = -\frac{1}{\delta^2} \sum_{k=1}^K n_k - \gamma \sum_{k=1}^K T_k^\delta [\ln(T_k)]^2 \tag{A8}$$

The second derivatives can be used to obtain estimates of the asymptotic variance of estimates of γ and δ using Fisher information evaluated at the parameter estimates.

(Crowder, 1991)

APPENDIX D. VISUAL BASIC FOR APPLICATIONS CODING

```
Sub CBM()  
  
    ' CBM Macro  
    ' Macro recorded 3/31/2006 by Stephen E. Gauthier  
    '  
    ' Documentation: LT Jason Kratz (NPS student) provided exceptional  
    ' assistance with this code by proofreading and finding many ways to  
    ' improve upon it's processing speed.  
  
    'This keeps workbook from updating every iteration  
    Application.ScreenUpdating = False  
    With Application  
        .Calculation = xlManual  
        .MaxChange = 0.001  
    End With  
    ActiveWorkbook.PrecisionAsDisplayed = False  
  
    'This computes Theta L and sets number of missions to 1250  
    Sheets("Legacy Process").Select  
    NumberMissions = 1250  
    NewMissionLength = 0  
    Worksheets("Legacy Process").Range(Cells(8, 1), Cells(7 +  
    NumberMissions, 1)).ClearContents  
    Dim ThreeJArray(9) As Double  
    Dim FourJArray(9) As Double  
  
    For j = 1 To 9  
        ThreeJArray(j) = Worksheets("Legacy Process").Cells(3, j)  
        FourJArray(j) = Worksheets("Legacy Process").Cells(4, j)  
    Next j  
  
    For i = 1 To NumberMissions  
        NewMissionLength = NewMissionLength + 4  
  
        For j = 1 To 5  
            If ThreeJArray(j) = 0 Then  
                Worksheets("Legacy Process").Cells(7 + i, 1) = FourJArray(1)  
            End If  
  
            If ThreeJArray(j) > 0 Then  
                multiplier = 0  
                multiplier =  
Application.WorksheetFunction.RoundDown(NewMissionLength /  
ThreeJArray(j), 0)  
                Worksheets("Legacy Process").Cells(1, 1) = multiplier  
            End If  
  
            If NewMissionLength = multiplier * ThreeJArray(j) Then  
                Worksheets("Legacy Process").Cells(7 + i, 1) = FourJArray(j)  
  
            ElseIf NewMissionLength - 1 = multiplier * ThreeJArray(j) Then  
                Worksheets("Legacy Process").Cells(7 + i, 1) = FourJArray(j)  
  
            ElseIf NewMissionLength - 2 = multiplier * ThreeJArray(j) Then
```

```

        Worksheets("Legacy Process").Cells(7 + i, 1) = FourJArray(j)

    ElseIf NewMissionLength - 3 = multiplier * ThreeJArray(j) Then
        Worksheets("Legacy Process").Cells(7 + i, 1) = FourJArray(j)
    End If

Next j

Next i

'This clears Data Worksheet below Row 24 and left of and including
Column 36
Sheets("Data").Select
M = NumberMissions
N = 36
Worksheets("Data").Range(Cells(25, 1), Cells(24 + M, N)).ClearContents

'This sets the number of iterations to perform
Replications = Worksheets("RVs").Cells(1, 2)
For v = 1 To Replications
    Calculate

'This clears N, M, R, and AS Columns of Legacy Process Worksheet
Sheets("Legacy Process").Select
N = 3
Worksheets("Legacy Process").Range(Cells(8, 12), Cells(7 + M, 11 +
N)).ClearContents
Worksheets("Legacy Process").Range(Cells(8, 24), Cells(7 + M, 23 +
N)).ClearContents
Worksheets("Legacy Process").Range(Cells(8, 35), Cells(7 + M, 34 +
N)).ClearContents
Worksheets("Legacy Process").Range(Cells(8, 46), Cells(7 + M, 45 +
N)).ClearContents

'This computes Sum of Dij and Rij for cases <= and > M
Sheets("Legacy Process").Select
NCount = 0
RTime = 0
N = 7
    For i = 1 To M
        If Worksheets("Legacy Process").Cells(7 + i, 4) > 0 Then
            NewNCount = 0
            NCount = 0
            NewNCount2 = 0
            NCount2 = 0
            NewNCount3 = 0
            NCount3 = 0
            NewNCount4 = 0
            NCount4 = 0
            NewRTime = 0
            RTime = 0
            NewRTime2 = 0
            RTime2 = 0
            NewASTime = 0
            ASTime = 0
            ASTime2 = 0

```

```

NewASTime2 = 0
temp2 = Worksheets("Legacy Process").Cells(7 + i, 2)

For j = 1 To N
    temp4 = Worksheets("Legacy Process").Cells(7 + i, 4 + j)
    temp16 = Worksheets("Legacy Process").Cells(7 + i, 16 + j)
    temp27 = Worksheets("Legacy Process").Cells(7 + i, 27 + j)
    temp38 = Worksheets("Legacy Process").Cells(7 + i, 38 + j)

    If temp4 < temp16 Then
        If temp4 > 0 And temp2 + temp4 <= M + 1 Then
            NewNCount = 1
            NCount = NewNCount + NCount
        End If
        If temp4 > 0 And temp2 + temp4 > M + 1 Then
            NewNCount2 = 1
            NCount2 = NewNCount2 + NCount2
        End If
        If temp2 + temp4 <= NumberMissions + 1 Then
            NewRTime = temp27
            RTime = NewRTime + RTime
            NewASTime = temp38
            ASTime = NewASTime + ASTime
        End If
        If temp2 + temp4 > NumberMissions + 1 Then
            NewRTime2 = temp27
            RTime2 = NewRTime2 + RTime2
            NewASTime2 = temp38
            ASTime2 = NewASTime2 + ASTime2
        End If
    Else
        If temp16 > 0 And temp2 + temp16 <= M + 1 Then
            NewNCount3 = 1
            NCount3 = NewNCount3 + NCount3
        End If
        If temp16 > 0 And temp2 + temp16 > M + 1 Then
            NewNCount4 = 1
            NCount4 = NewNCount4 + NCount4
        End If
        If temp2 + temp16 <= NumberMissions + 1 Then
            NewRTime = temp27
            RTime = NewRTime + RTime
            NewASTime = temp38
            ASTime = NewASTime + ASTime
        End If
        If temp2 + temp16 > NumberMissions + 1 Then
            NewRTime2 = temp27
            RTime2 = NewRTime2 + RTime2
            NewASTime2 = temp38
            ASTime2 = NewASTime2 + ASTime2
        End If
    End If
End If

Next j

Worksheets("Legacy Process").Cells(7 + i, 12) = NCount
Worksheets("Legacy Process").Cells(7 + i, 13) = NCount2

```

```

Worksheets("Legacy Process").Cells(7 + i, 24) = NCount3
Worksheets("Legacy Process").Cells(7 + i, 25) = NCount4
Worksheets("Legacy Process").Cells(7 + i, 35) = RTime
Worksheets("Legacy Process").Cells(7 + i, 36) = RTime2
Worksheets("Legacy Process").Cells(7 + i, 46) = ATime
Worksheets("Legacy Process").Cells(7 + i, 47) = ATime2

End If
Worksheets("Legacy Process").Cells(7 + i, 14) =
Worksheets("Legacy Process").Cells(7 + i, 12) + Worksheets("Legacy
Process").Cells(7 + i, 13)
Worksheets("Legacy Process").Cells(7 + i, 26) =
Worksheets("Legacy Process").Cells(7 + i, 24) + Worksheets("Legacy
Process").Cells(7 + i, 25)
Worksheets("Legacy Process").Cells(7 + i, 37) =
Worksheets("Legacy Process").Cells(7 + i, 35) + Worksheets("Legacy
Process").Cells(7 + i, 36)
Worksheets("Legacy Process").Cells(7 + i, 48) =
Worksheets("Legacy Process").Cells(7 + i, 46) + Worksheets("Legacy
Process").Cells(7 + i, 47)
Next i

'This determines if there was an immediate Mission Abort
Sheets("RVs").Select

For i = 1 To M
    If Application.WorksheetFunction.CountIf(Range(Cells(4 + i, 6),
Cells(4 + i, 12)), "= 1") >= 1 Then
        Sheets("Legacy Process").Select
        Worksheets("Legacy Process").Cells(7 + i, 16) = 1
        Sheets("RVs").Select
    Else
        Worksheets("Legacy Process").Cells(7 + i, 16) = 0
    End If
Next i

'This produces the summed outputs for the Legacy Spreadsheet
Sheets("Legacy Process").Select
Worksheets("Legacy Process").Cells(1, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 12), Cells(7 + M,
12)))
Worksheets("Legacy Process").Cells(2, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 13), Cells(7 + M,
13)))
Worksheets("Legacy Process").Cells(3, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 14), Cells(7 + M,
14)))
Worksheets("Legacy Process").Cells(4, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 24), Cells(7 + M,
24)))
Worksheets("Legacy Process").Cells(5, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 25), Cells(7 + M,
25)))
Worksheets("Legacy Process").Cells(6, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 26), Cells(7 + M,
26)))

```

```

Worksheets("Legacy Process").Cells(1, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 35), Cells(7 + M,
35)))
Worksheets("Legacy Process").Cells(2, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 36), Cells(7 + M,
36)))
Worksheets("Legacy Process").Cells(3, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 37), Cells(7 + M,
37)))
Worksheets("Legacy Process").Cells(4, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 46), Cells(7 + M,
46)))
Worksheets("Legacy Process").Cells(5, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 47), Cells(7 + M,
47)))
Worksheets("Legacy Process").Cells(6, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 48), Cells(7 + M,
48)))

'This clears Summed D, M, R, and AS Columns of CBM+ Process Worksheet
Sheets("CBM+ Process").Select
N = 3
Worksheets("CBM+ Process").Range(Cells(8, 12), Cells(7 + M, 11 +
N)).ClearContents
Worksheets("CBM+ Process").Range(Cells(8, 24), Cells(7 + M, 23 +
N)).ClearContents
Worksheets("CBM+ Process").Range(Cells(8, 35), Cells(7 + M, 34 +
N)).ClearContents
Worksheets("CBM+ Process").Range(Cells(8, 46), Cells(7 + M, 45 +
N)).ClearContents

'This computes Sum of Dij and Sum of Rij for cases <= and > M
Sheets("CBM+ Process").Select
NCount = 0
M = NumberMissions
N = 7

For i = 1 To M
    If Worksheets("CBM+ Process").Cells(7 + i, 4) > 0 Then
        NewNCount = 0
        NCount = 0
        NewNCount2 = 0
        NCount2 = 0
        NewNCount3 = 0
        NCount3 = 0
        NewNCount4 = 0
        NCount4 = 0
        NewRTime = 0
        RTime = 0
        NewRTime2 = 0
        RTime2 = 0
        NewASTime = 0
        ASTime = 0
        ASTime2 = 0
        NewASTime2 = 0
    End If
End For

```

```

temp2 = Worksheets("CBM+ Process").Cells(7 + i, 2)

For j = 1 To N
    temp4 = Worksheets("CBM+ Process").Cells(7 + i, 4 + j)
    temp16 = Worksheets("CBM+ Process").Cells(7 + i, 16 + j)
    temp27 = Worksheets("CBM+ Process").Cells(7 + i, 27 + j)
    temp38 = Worksheets("CBM+ Process").Cells(7 + i, 38 + j)

    If temp4 < temp16 Then
        If temp4 > 0 And temp2 + temp4 <= M + 1 Then
            NewNCount = 1
            NCount = NewNCount + NCount
        End If
        If temp4 > 0 And temp2 + temp4 > M + 1 Then
            NewNCount2 = 1
            NCount2 = NewNCount2 + NCount2
        End If
        If temp2 + temp4 <= NumberMissions + 1 Then
            NewRTime = temp27
            RTime = NewRTime + RTime
            NewASTime = temp38
            ASTime = NewASTime + ASTime
        End If
        If temp2 + temp4 > NumberMissions + 1 Then
            NewRTime2 = temp27
            RTime2 = NewRTime2 + RTime2
            NewASTime2 = temp38
            ASTime2 = NewASTime2 + ASTime2
        End If
    Else
        If temp16 > 0 And temp2 + temp16 <= M + 1 Then
            NewNCount3 = 1
            NCount3 = NewNCount3 + NCount3
        End If
        If temp16 > 0 And temp2 + temp16 > M + 1 Then
            NewNCount4 = 1
            NCount4 = NewNCount4 + NCount4
        End If
        If temp2 + temp16 <= NumberMissions + 1 Then
            NewRTime = temp27
            RTime = NewRTime + RTime
            NewASTime = temp38
            ASTime = NewASTime + ASTime
        End If
        If temp2 + temp16 > NumberMissions + 1 Then
            NewRTime2 = temp27
            RTime2 = NewRTime2 + RTime2
            NewASTime2 = temp38
            ASTime2 = NewASTime2 + ASTime2
        End If
    End If
End If

Next j
Worksheets("CBM+ Process").Cells(7 + i, 12) = NCount
Worksheets("CBM+ Process").Cells(7 + i, 13) = NCount2
Worksheets("CBM+ Process").Cells(7 + i, 24) = NCount3
Worksheets("CBM+ Process").Cells(7 + i, 25) = NCount4

```

```

Worksheets("CBM+ Process").Cells(7 + i, 35) = RTime
Worksheets("CBM+ Process").Cells(7 + i, 36) = RTime2
Worksheets("CBM+ Process").Cells(7 + i, 46) = ATime
Worksheets("CBM+ Process").Cells(7 + i, 47) = ATime2

End If
Worksheets("CBM+ Process").Cells(7 + i, 14) = Worksheets("CBM+
Process").Cells(7 + i, 12) + Worksheets("CBM+ Process").Cells(7 + i,
13)
Worksheets("CBM+ Process").Cells(7 + i, 26) = Worksheets("CBM+
Process").Cells(7 + i, 24) + Worksheets("CBM+ Process").Cells(7 + i,
25)
Worksheets("CBM+ Process").Cells(7 + i, 37) = Worksheets("CBM+
Process").Cells(7 + i, 35) + Worksheets("CBM+ Process").Cells(7 + i,
36)
Worksheets("CBM+ Process").Cells(7 + i, 48) = Worksheets("CBM+
Process").Cells(7 + i, 46) + Worksheets("CBM+ Process").Cells(7 + i,
47)
Worksheets("CBM+ Process").Cells(7 + i, 52) = Worksheets("CBM+
Process").Cells(7 + i, 37) + Worksheets("CBM+ Process").Cells(7 + i,
51)

Next i

'This determines if there was an immediate Mission Abort
Sheets("RVs").Select

For i = 1 To M
    If Application.WorksheetFunction.CountIf(Range(Cells(4 + i, 6),
Cells(4 + i, 12)), "= 1") >= 1 Then
        Sheets("CBM+ Process").Select
        Worksheets("CBM+ Process").Cells(7 + i, 16) = 1
        Sheets("RVs").Select
    Else
        Worksheets("CBM+ Process").Cells(7 + i, 16) = 0
    End If
Next i

'This produces the summed outputs for the CBM+ Spreadsheet
Sheets("CBM+ Process").Select

Worksheets("CBM+ Process").Cells(1, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 12), Cells(7 + M,
12)))
Worksheets("CBM+ Process").Cells(2, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 13), Cells(7 + M,
13)))
Worksheets("CBM+ Process").Cells(3, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 14), Cells(7 + M,
14)))
Worksheets("CBM+ Process").Cells(4, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 24), Cells(7 + M,
24)))
Worksheets("CBM+ Process").Cells(5, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 25), Cells(7 + M,
25)))

```

```

Worksheets("CBM+ Process").Cells(6, 15) =
Application.WorksheetFunction.Sum(Range(Cells(8, 26), Cells(7 + M,
26)))
Worksheets("CBM+ Process").Cells(1, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 35), Cells(7 + M,
35)))
Worksheets("CBM+ Process").Cells(2, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 36), Cells(7 + M,
36)))
Worksheets("CBM+ Process").Cells(3, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 37), Cells(7 + M,
37)))
Worksheets("CBM+ Process").Cells(4, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 46), Cells(7 + M,
46)))
Worksheets("CBM+ Process").Cells(5, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 47), Cells(7 + M,
47)))
Worksheets("CBM+ Process").Cells(6, 18) =
Application.WorksheetFunction.Sum(Range(Cells(8, 48), Cells(7 + M,
48)))
Worksheets("CBM+ Process").Cells(1, 21) =
Application.WorksheetFunction.Sum(Range(Cells(8, 50), Cells(7 + M,
50)))
Worksheets("CBM+ Process").Cells(2, 21) =
Application.WorksheetFunction.Sum(Range(Cells(8, 51), Cells(7 + M,
51)))
Worksheets("CBM+ Process").Cells(3, 21) =
Application.WorksheetFunction.Sum(Range(Cells(8, 52), Cells(7 + M,
52)))

```

```

'This transposes data onto Data Worksheet
Sheets("Legacy Process").Select
Range(Cells(1, 15), Cells(6, 15)).Select
Selection.Copy
Sheets("Data").Select
Range(Cells(24 + v, 1), Cells(24 + v, 6)).Select
Selection.PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _
    False, Transpose:=True

```

```

Sheets("Legacy Process").Select
Range(Cells(1, 18), Cells(6, 18)).Select
Selection.Copy
Sheets("Data").Select
Range(Cells(24 + v, 7), Cells(24 + v, 12)).Select
Selection.PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _
    False, Transpose:=True

```

```

'This transposes data onto Data Worksheet
Sheets("CBM+ Process").Select
Range(Cells(1, 15), Cells(6, 15)).Select
Selection.Copy
Sheets("Data").Select
Range(Cells(24 + v, 22), Cells(24 + v, 27)).Select

```

```

Selection.PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _
    False, Transpose:=True

Sheets("CBM+ Process").Select
Range(Cells(1, 18), Cells(6, 18)).Select
Selection.Copy
Sheets("Data").Select
Range(Cells(24 + v, 28), Cells(24 + v, 33)).Select
Selection.PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _
    False, Transpose:=True

Sheets("CBM+ Process").Select
Range(Cells(1, 21), Cells(3, 21)).Select
Selection.Copy
Sheets("Data").Select
Range(Cells(24 + v, 34), Cells(24 + v, 36)).Select
Selection.PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _
    False, Transpose:=True

Next v

'This determines means and CIs
Sheets("Data").Select
Worksheets("Data").Cells(2, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 1), Cells(24 + v,
1)))
Worksheets("Data").Cells(3, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 2), Cells(24 + v,
2)))
Worksheets("Data").Cells(4, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 3), Cells(24 + v,
3)))
Worksheets("Data").Cells(5, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 4), Cells(24 + v,
4)))
Worksheets("Data").Cells(6, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 5), Cells(24 + v,
5)))
Worksheets("Data").Cells(7, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 6), Cells(24 + v,
6)))
Worksheets("Data").Cells(8, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 7), Cells(24 + v,
7)))
Worksheets("Data").Cells(9, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 8), Cells(24 + v,
8)))
Worksheets("Data").Cells(10, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 9), Cells(24 + v,
9)))
Worksheets("Data").Cells(11, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 10), Cells(24 +
v, 10)))

```

```

Worksheets("Data").Cells(12, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 11), Cells(24 +
v, 11)))
Worksheets("Data").Cells(13, 3) =
Application.WorksheetFunction.Average(Range(Cells(25, 12), Cells(24 +
v, 12)))

Worksheets("Data").Cells(2, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 22), Cells(24 +
v, 22)))
Worksheets("Data").Cells(3, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 23), Cells(24 +
v, 23)))
Worksheets("Data").Cells(4, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 24), Cells(24 +
v, 24)))
Worksheets("Data").Cells(5, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 25), Cells(24 +
v, 25)))
Worksheets("Data").Cells(6, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 26), Cells(24 +
v, 26)))
Worksheets("Data").Cells(7, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 27), Cells(24 +
v, 27)))
Worksheets("Data").Cells(8, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 28), Cells(24 +
v, 28)))
Worksheets("Data").Cells(9, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 29), Cells(24 +
v, 29)))
Worksheets("Data").Cells(10, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 30), Cells(24 +
v, 30)))
Worksheets("Data").Cells(11, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 31), Cells(24 +
v, 31)))
Worksheets("Data").Cells(12, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 32), Cells(24 +
v, 32)))
Worksheets("Data").Cells(13, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 33), Cells(24 +
v, 33)))
Worksheets("Data").Cells(14, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 34), Cells(24 +
v, 34)))
Worksheets("Data").Cells(15, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 35), Cells(24 +
v, 35)))
Worksheets("Data").Cells(16, 11) =
Application.WorksheetFunction.Average(Range(Cells(25, 36), Cells(24 +
v, 36)))

```

```

If Worksheets("Data").Cells(2, 3) > 0 Then

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```

Worksheets("Data").Cells(2, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 1), Cells(24 + v,
1)))
Else: Worksheets("Data").Cells(2, 5) = 0
End If

If Worksheets("Data").Cells(3, 3) > 0 Then
Worksheets("Data").Cells(3, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 2), Cells(24 + v,
2)))
Else: Worksheets("Data").Cells(3, 5) = 0
End If

If Worksheets("Data").Cells(4, 3) > 0 Then
Worksheets("Data").Cells(4, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 3), Cells(24 + v,
3)))
Else: Worksheets("Data").Cells(4, 5) = 0
End If

If Worksheets("Data").Cells(5, 3) > 0 Then
Worksheets("Data").Cells(5, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 4), Cells(24 + v,
4)))
Else: Worksheets("Data").Cells(5, 5) = 0
End If

If Worksheets("Data").Cells(6, 3) > 0 Then
Worksheets("Data").Cells(6, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 5), Cells(24 + v,
5)))
Else: Worksheets("Data").Cells(6, 5) = 0
End If

If Worksheets("Data").Cells(7, 3) > 0 Then
Worksheets("Data").Cells(7, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 6), Cells(24 + v,
6)))
Else: Worksheets("Data").Cells(7, 5) = 0
End If

If Worksheets("Data").Cells(8, 3) > 0 Then
Worksheets("Data").Cells(8, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 7), Cells(24 + v,
7)))
Else: Worksheets("Data").Cells(8, 5) = 0
End If

If Worksheets("Data").Cells(9, 3) > 0 Then
Worksheets("Data").Cells(9, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 8), Cells(24 + v,
8)))
Else: Worksheets("Data").Cells(9, 5) = 0
End If

If Worksheets("Data").Cells(10, 3) > 0 Then

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Worksheets("Data").Cells(10, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 9), Cells(24 + v,
9)))
Else: Worksheets("Data").Cells(10, 5) = 0
End If

If Worksheets("Data").Cells(11, 3) > 0 Then
Worksheets("Data").Cells(11, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 10), Cells(24 + v,
10)))
Else: Worksheets("Data").Cells(11, 5) = 0
End If

If Worksheets("Data").Cells(12, 3) > 0 Then
Worksheets("Data").Cells(12, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 11), Cells(24 + v,
11)))
Else: Worksheets("Data").Cells(12, 5) = 0
End If

If Worksheets("Data").Cells(13, 3) > 0 Then
Worksheets("Data").Cells(13, 5) =
Application.WorksheetFunction.StDev(Range(Cells(25, 12), Cells(24 + v,
12)))
Else: Worksheets("Data").Cells(13, 5) = 0
End If

If Worksheets("Data").Cells(2, 11) > 0 Then
Worksheets("Data").Cells(2, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 22), Cells(24 + v,
22)))
Else: Worksheets("Data").Cells(2, 13) = 0
End If

If Worksheets("Data").Cells(3, 11) > 0 Then
Worksheets("Data").Cells(3, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 23), Cells(24 + v,
23)))
Else: Worksheets("Data").Cells(3, 13) = 0
End If

If Worksheets("Data").Cells(4, 11) > 0 Then
Worksheets("Data").Cells(4, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 24), Cells(24 + v,
24)))
Else: Worksheets("Data").Cells(4, 13) = 0
End If

If Worksheets("Data").Cells(5, 11) > 0 Then
Worksheets("Data").Cells(5, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 25), Cells(24 + v,
25)))
Else: Worksheets("Data").Cells(5, 13) = 0
End If

If Worksheets("Data").Cells(6, 11) > 0 Then

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```

Worksheets("Data").Cells(6, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 26), Cells(24 + v,
26)))
Else: Worksheets("Data").Cells(6, 13) = 0
End If

If Worksheets("Data").Cells(7, 11) > 0 Then
Worksheets("Data").Cells(7, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 27), Cells(24 + v,
27)))
Else: Worksheets("Data").Cells(7, 13) = 0
End If

If Worksheets("Data").Cells(8, 11) > 0 Then
Worksheets("Data").Cells(8, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 28), Cells(24 + v,
28)))
Else: Worksheets("Data").Cells(8, 13) = 0
End If

If Worksheets("Data").Cells(9, 11) > 0 Then
Worksheets("Data").Cells(9, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 29), Cells(24 + v,
29)))
Else: Worksheets("Data").Cells(9, 13) = 0
End If

If Worksheets("Data").Cells(10, 11) > 0 Then
Worksheets("Data").Cells(10, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 30), Cells(24 + v,
30)))
Else: Worksheets("Data").Cells(10, 13) = 0
End If

If Worksheets("Data").Cells(11, 11) > 0 Then
Worksheets("Data").Cells(11, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 31), Cells(24 + v,
31)))
Else: Worksheets("Data").Cells(11, 13) = 0
End If

If Worksheets("Data").Cells(12, 11) > 0 Then
Worksheets("Data").Cells(12, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 32), Cells(24 + v,
32)))
Else: Worksheets("Data").Cells(12, 13) = 0
End If

If Worksheets("Data").Cells(13, 11) > 0 Then
Worksheets("Data").Cells(13, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 33), Cells(24 + v,
33)))
Else: Worksheets("Data").Cells(13, 13) = 0
End If

If Worksheets("Data").Cells(14, 11) > 0 Then

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```

Worksheets("Data").Cells(14, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 34), Cells(24 + v,
34)))
Else: Worksheets("Data").Cells(14, 13) = 0
End If

If Worksheets("Data").Cells(15, 11) > 0 Then
Worksheets("Data").Cells(15, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 35), Cells(24 + v,
35)))
Else: Worksheets("Data").Cells(15, 13) = 0
End If

If Worksheets("Data").Cells(16, 11) > 0 Then
Worksheets("Data").Cells(16, 13) =
Application.WorksheetFunction.StDev(Range(Cells(25, 36), Cells(24 + v,
36)))
Else: Worksheets("Data").Cells(16, 13) = 0
End If

If Worksheets("Data").Cells(2, 5) > 0 Then
Worksheets("Data").Cells(2, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(2, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(2, 5), (v - 1)), 0)
Worksheets("Data").Cells(2, 8) = Worksheets("Data").Cells(2, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(2, 5), v - 1)
Else
Worksheets("Data").Cells(2, 7) = 0
Worksheets("Data").Cells(2, 8) = 0
End If

If Worksheets("Data").Cells(3, 5) > 0 Then
Worksheets("Data").Cells(3, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(3, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(3, 5), (v - 1)), 0)
Worksheets("Data").Cells(3, 8) = Worksheets("Data").Cells(3, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(3, 5), v - 1)
Else
Worksheets("Data").Cells(3, 7) = 0
Worksheets("Data").Cells(3, 8) = 0
End If

If Worksheets("Data").Cells(4, 5) > 0 Then
Worksheets("Data").Cells(4, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(4, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(4, 5), (v - 1)), 0)
Worksheets("Data").Cells(4, 8) = Worksheets("Data").Cells(4, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(4, 5), v - 1)
Else
Worksheets("Data").Cells(4, 7) = 0
Worksheets("Data").Cells(4, 8) = 0

```

```

End If

If Worksheets("Data").Cells(5, 5) > 0 Then
    Worksheets("Data").Cells(5, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(5, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(5, 5), (v - 1)), 0)
    Worksheets("Data").Cells(5, 8) = Worksheets("Data").Cells(5, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(5, 5), v - 1)
Else
    Worksheets("Data").Cells(5, 7) = 0
    Worksheets("Data").Cells(5, 8) = 0
End If

If Worksheets("Data").Cells(6, 5) > 0 Then
    Worksheets("Data").Cells(6, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(6, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(6, 5), (v - 1)), 0)
    Worksheets("Data").Cells(6, 8) = Worksheets("Data").Cells(6, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(6, 5), v - 1)
Else
    Worksheets("Data").Cells(6, 7) = 0
    Worksheets("Data").Cells(6, 8) = 0
End If

If Worksheets("Data").Cells(7, 5) > 0 Then
    Worksheets("Data").Cells(7, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(7, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(7, 5), (v - 1)), 0)
    Worksheets("Data").Cells(7, 8) = Worksheets("Data").Cells(7, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(7, 5), v - 1)
Else
    Worksheets("Data").Cells(7, 7) = 0
    Worksheets("Data").Cells(7, 8) = 0
End If

If Worksheets("Data").Cells(8, 5) > 0 Then
    Worksheets("Data").Cells(8, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(8, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(8, 5), (v - 1)), 0)
    Worksheets("Data").Cells(8, 8) = Worksheets("Data").Cells(8, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(8, 5), v - 1)
Else
    Worksheets("Data").Cells(8, 7) = 0
    Worksheets("Data").Cells(8, 8) = 0
End If

If Worksheets("Data").Cells(9, 5) > 0 Then
    Worksheets("Data").Cells(9, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(9, 3) -

```

```

Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(9, 5), (v - 1)), 0)
    Worksheets("Data").Cells(9, 8) = Worksheets("Data").Cells(9, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(9, 5), v - 1)
    Else
        Worksheets("Data").Cells(9, 7) = 0
        Worksheets("Data").Cells(9, 8) = 0
End If

If Worksheets("Data").Cells(10, 5) > 0 Then
    Worksheets("Data").Cells(10, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(10, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(10, 5), (v - 1)), 0)
    Worksheets("Data").Cells(10, 8) = Worksheets("Data").Cells(10, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(10, 5), v - 1)
    Else
        Worksheets("Data").Cells(10, 7) = 0
        Worksheets("Data").Cells(10, 8) = 0
End If

If Worksheets("Data").Cells(11, 5) > 0 Then
    Worksheets("Data").Cells(11, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(11, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(11, 5), (v - 1)), 0)
    Worksheets("Data").Cells(11, 8) = Worksheets("Data").Cells(11, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(11, 5), v - 1)
    Else
        Worksheets("Data").Cells(11, 7) = 0
        Worksheets("Data").Cells(11, 8) = 0
End If

If Worksheets("Data").Cells(12, 5) > 0 Then
    Worksheets("Data").Cells(12, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(12, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(12, 5), (v - 1)), 0)
    Worksheets("Data").Cells(12, 8) = Worksheets("Data").Cells(12, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(12, 5), v - 1)
    Else
        Worksheets("Data").Cells(12, 7) = 0
        Worksheets("Data").Cells(12, 8) = 0
End If

If Worksheets("Data").Cells(13, 5) > 0 Then
    Worksheets("Data").Cells(13, 7) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(13, 3) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(13, 5), (v - 1)), 0)
    Worksheets("Data").Cells(13, 8) = Worksheets("Data").Cells(13, 3) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(13, 5), v - 1)

```

```

        Else
            Worksheets("Data").Cells(13, 7) = 0
            Worksheets("Data").Cells(13, 8) = 0
        End If

    If Worksheets("Data").Cells(2, 13) > 0 Then
        Worksheets("Data").Cells(2, 15) =
        Application.WorksheetFunction.Max(Worksheets("Data").Cells(2, 11) -
        Application.WorksheetFunction.Confidence(0.05,
        Worksheets("Data").Cells(2, 13), (v - 1)), 0)
        Worksheets("Data").Cells(2, 16) = Worksheets("Data").Cells(2, 11) +
        Application.WorksheetFunction.Confidence(0.05,
        Worksheets("Data").Cells(2, 13), v - 1)
    Else
        Worksheets("Data").Cells(2, 15) = 0
        Worksheets("Data").Cells(2, 16) = 0
    End If

    If Worksheets("Data").Cells(3, 13) > 0 Then
        Worksheets("Data").Cells(3, 15) =
        Application.WorksheetFunction.Max(Worksheets("Data").Cells(3, 11) -
        Application.WorksheetFunction.Confidence(0.05,
        Worksheets("Data").Cells(3, 13), (v - 1)), 0)
        Worksheets("Data").Cells(3, 16) = Worksheets("Data").Cells(3, 11) +
        Application.WorksheetFunction.Confidence(0.05,
        Worksheets("Data").Cells(3, 13), v - 1)
    Else
        Worksheets("Data").Cells(3, 15) = 0
        Worksheets("Data").Cells(3, 16) = 0
    End If

    If Worksheets("Data").Cells(4, 13) > 0 Then
        Worksheets("Data").Cells(4, 15) =
        Application.WorksheetFunction.Max(Worksheets("Data").Cells(4, 11) -
        Application.WorksheetFunction.Confidence(0.05,
        Worksheets("Data").Cells(4, 13), (v - 1)), 0)
        Worksheets("Data").Cells(4, 16) = Worksheets("Data").Cells(4, 11) +
        Application.WorksheetFunction.Confidence(0.05,
        Worksheets("Data").Cells(4, 13), v - 1)
    Else
        Worksheets("Data").Cells(4, 15) = 0
        Worksheets("Data").Cells(4, 16) = 0
    End If

    If Worksheets("Data").Cells(5, 13) > 0 Then
        Worksheets("Data").Cells(5, 15) =
        Application.WorksheetFunction.Max(Worksheets("Data").Cells(5, 11) -
        Application.WorksheetFunction.Confidence(0.05,
        Worksheets("Data").Cells(5, 13), (v - 1)), 0)
        Worksheets("Data").Cells(5, 16) = Worksheets("Data").Cells(5, 11) +
        Application.WorksheetFunction.Confidence(0.05,
        Worksheets("Data").Cells(5, 13), v - 1)
    Else
        Worksheets("Data").Cells(5, 15) = 0
        Worksheets("Data").Cells(5, 16) = 0
    End If

```

```

If Worksheets("Data").Cells(6, 13) > 0 Then
    Worksheets("Data").Cells(6, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(6, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(6, 13), (v - 1)), 0)
    Worksheets("Data").Cells(6, 16) = Worksheets("Data").Cells(6, 11) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(6, 13), v - 1)
Else
    Worksheets("Data").Cells(6, 15) = 0
    Worksheets("Data").Cells(6, 16) = 0
End If

If Worksheets("Data").Cells(7, 13) > 0 Then
    Worksheets("Data").Cells(7, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(7, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(7, 13), (v - 1)), 0)
    Worksheets("Data").Cells(7, 16) = Worksheets("Data").Cells(7, 11) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(7, 13), v - 1)
Else
    Worksheets("Data").Cells(7, 15) = 0
    Worksheets("Data").Cells(7, 16) = 0
End If

If Worksheets("Data").Cells(8, 13) > 0 Then
    Worksheets("Data").Cells(8, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(8, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(8, 13), (v - 1)), 0)
    Worksheets("Data").Cells(8, 16) = Worksheets("Data").Cells(8, 11) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(8, 13), v - 1)
Else
    Worksheets("Data").Cells(8, 15) = 0
    Worksheets("Data").Cells(8, 16) = 0
End If

If Worksheets("Data").Cells(9, 13) > 0 Then
    Worksheets("Data").Cells(9, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(9, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(9, 13), (v - 1)), 0)
    Worksheets("Data").Cells(9, 16) = Worksheets("Data").Cells(9, 11) +
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(9, 13), v - 1)
Else
    Worksheets("Data").Cells(9, 15) = 0
    Worksheets("Data").Cells(9, 16) = 0
End If

If Worksheets("Data").Cells(10, 13) > 0 Then
    Worksheets("Data").Cells(10, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(10, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(10, 13), (v - 1)), 0)

```

```

Worksheets("Data").Cells(10, 16) = Worksheets("Data").Cells(10, 11)
+ Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(10, 13), v - 1)
Else
Worksheets("Data").Cells(10, 15) = 0
Worksheets("Data").Cells(10, 16) = 0
End If

If Worksheets("Data").Cells(11, 13) > 0 Then
Worksheets("Data").Cells(11, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(11, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(11, 13), (v - 1)), 0)
Worksheets("Data").Cells(11, 16) = Worksheets("Data").Cells(11, 11)
+ Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(11, 13), v - 1)
Else
Worksheets("Data").Cells(11, 15) = 0
Worksheets("Data").Cells(11, 16) = 0
End If

If Worksheets("Data").Cells(12, 13) > 0 Then
Worksheets("Data").Cells(12, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(12, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(12, 13), (v - 1)), 0)
Worksheets("Data").Cells(12, 16) = Worksheets("Data").Cells(12, 11)
+ Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(12, 13), v - 1)
Else
Worksheets("Data").Cells(12, 15) = 0
Worksheets("Data").Cells(12, 16) = 0
End If

If Worksheets("Data").Cells(13, 13) > 0 Then
Worksheets("Data").Cells(13, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(13, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(13, 13), (v - 1)), 0)
Worksheets("Data").Cells(13, 16) = Worksheets("Data").Cells(13, 11)
+ Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(13, 13), v - 1)
Else
Worksheets("Data").Cells(13, 15) = 0
Worksheets("Data").Cells(13, 16) = 0
End If

If Worksheets("Data").Cells(14, 13) > 0 Then
Worksheets("Data").Cells(14, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(14, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(14, 13), (v - 1)), 0)
Worksheets("Data").Cells(14, 16) = Worksheets("Data").Cells(14, 11)
+ Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(14, 13), v - 1)
Else
Worksheets("Data").Cells(14, 15) = 0

```

```

        Worksheets("Data").Cells(14, 16) = 0
End If

If Worksheets("Data").Cells(15, 13) > 0 Then
    Worksheets("Data").Cells(15, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(15, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(15, 13), (v - 1)), 0)
    Worksheets("Data").Cells(15, 16) = Worksheets("Data").Cells(15, 11)
+ Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(15, 13), v - 1)
Else
    Worksheets("Data").Cells(15, 15) = 0
    Worksheets("Data").Cells(15, 16) = 0
End If

If Worksheets("Data").Cells(16, 13) > 0 Then
    Worksheets("Data").Cells(16, 15) =
Application.WorksheetFunction.Max(Worksheets("Data").Cells(16, 11) -
Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(16, 13), (v - 1)), 0)
    Worksheets("Data").Cells(16, 16) = Worksheets("Data").Cells(16, 11)
+ Application.WorksheetFunction.Confidence(0.05,
Worksheets("Data").Cells(16, 13), v - 1)
Else
    Worksheets("Data").Cells(16, 15) = 0
    Worksheets("Data").Cells(16, 16) = 0
End Sub

```

APPENDIX E. STATISTICAL RESULTS FOR VARYING P_C

All table listed below were computed using 1,000 replications of the simulation.

Table A1 displays statistical summaries of the output from simulation of the number of mission aborts occurring as a result of 1,250 missions (5,000 flight hours) while varying P_C . The parameters of the beta distribution are as per Table 11; the parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$. This is data for Figure 6.

Table A1

| P _C | LEGACY PROCESS | | | | | | | | CBM+ PROCESS | | | | | | | |
|----------------|----------------|-------|------|-----|------|---------|------|------|--------------|-------|------|-----|------|---------|------|------|
| 0.10 | ΣAborts | Mean: | 4.70 | SD: | 2.14 | 95% CI: | 4.57 | 4.83 | ΣAborts | Mean: | 5.25 | SD: | 2.27 | 95% CI: | 5.11 | 5.39 |
| 0.20 | ΣAborts | Mean: | 4.53 | SD: | 2.11 | 95% CI: | 4.40 | 4.66 | ΣAborts | Mean: | 2.95 | SD: | 1.64 | 95% CI: | 2.85 | 3.06 |
| 0.30 | ΣAborts | Mean: | 4.57 | SD: | 2.07 | 95% CI: | 4.44 | 4.70 | ΣAborts | Mean: | 1.91 | SD: | 1.40 | 95% CI: | 1.83 | 2.00 |
| 0.40 | ΣAborts | Mean: | 4.49 | SD: | 2.09 | 95% CI: | 4.36 | 4.62 | ΣAborts | Mean: | 1.32 | SD: | 1.11 | 95% CI: | 1.25 | 1.39 |
| 0.50 | ΣAborts | Mean: | 4.45 | SD: | 2.15 | 95% CI: | 4.32 | 4.58 | ΣAborts | Mean: | 0.93 | SD: | 0.97 | 95% CI: | 0.87 | 0.99 |
| 0.60 | ΣAborts | Mean: | 4.55 | SD: | 2.13 | 95% CI: | 4.42 | 4.68 | ΣAborts | Mean: | 0.73 | SD: | 0.87 | 95% CI: | 0.67 | 0.78 |
| 0.70 | ΣAborts | Mean: | 4.56 | SD: | 2.06 | 95% CI: | 4.44 | 4.69 | ΣAborts | Mean: | 0.53 | SD: | 0.74 | 95% CI: | 0.48 | 0.57 |
| 0.80 | ΣAborts | Mean: | 4.52 | SD: | 2.08 | 95% CI: | 4.39 | 4.65 | ΣAborts | Mean: | 0.46 | SD: | 0.68 | 95% CI: | 0.42 | 0.50 |
| 0.90 | ΣAborts | Mean: | 4.51 | SD: | 2.08 | 95% CI: | 4.38 | 4.64 | ΣAborts | Mean: | 0.36 | SD: | 0.61 | 95% CI: | 0.32 | 0.40 |
| 0.99 | ΣAborts | Mean: | 4.53 | SD: | 2.14 | 95% CI: | 4.40 | 4.66 | ΣAborts | Mean: | 0.32 | SD: | 0.58 | 95% CI: | 0.28 | 0.35 |

Table A2 displays the statistical summaries of the output from simulation of the repair times occurring as a result of 1,250 missions (5,000 flight hours) while varying P_C . The parameters of the beta distribution are as per Table 11; the parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$. This is data for Figure 7.

Table A2

| P _c | LEGACY PROCESS | | | | | | | CBM+ PROCESS | | | | | | | | |
|----------------|----------------|-------|-------|-----|-------|---------|-------|--------------|----|-------|-------|-----|-------|---------|-------|-------|
| 0.10 | ΣR | Mean: | 76.13 | SD: | 27.36 | 95% CI: | 74.44 | 77.83 | ΣR | Mean: | 80.75 | SD: | 29.17 | 95% CI: | 78.94 | 82.55 |
| 0.20 | ΣR | Mean: | 75.06 | SD: | 26.71 | 95% CI: | 73.40 | 76.71 | ΣR | Mean: | 66.58 | SD: | 23.92 | 95% CI: | 65.10 | 68.07 |
| 0.30 | ΣR | Mean: | 75.94 | SD: | 27.24 | 95% CI: | 74.25 | 77.63 | ΣR | Mean: | 59.27 | SD: | 23.04 | 95% CI: | 57.84 | 60.70 |
| 0.40 | ΣR | Mean: | 74.65 | SD: | 27.13 | 95% CI: | 72.97 | 76.33 | ΣR | Mean: | 54.83 | SD: | 20.85 | 95% CI: | 53.54 | 56.13 |
| 0.50 | ΣR | Mean: | 75.29 | SD: | 26.56 | 95% CI: | 73.65 | 76.94 | ΣR | Mean: | 51.40 | SD: | 19.09 | 95% CI: | 50.22 | 52.58 |
| 0.60 | ΣR | Mean: | 75.02 | SD: | 27.49 | 95% CI: | 73.32 | 76.73 | ΣR | Mean: | 46.68 | SD: | 18.23 | 95% CI: | 45.55 | 47.81 |
| 0.70 | ΣR | Mean: | 76.24 | SD: | 26.60 | 95% CI: | 74.59 | 77.89 | ΣR | Mean: | 44.07 | SD: | 17.29 | 95% CI: | 42.99 | 45.14 |
| 0.80 | ΣR | Mean: | 75.84 | SD: | 28.04 | 95% CI: | 74.10 | 77.58 | ΣR | Mean: | 40.75 | SD: | 16.05 | 95% CI: | 39.75 | 41.74 |
| 0.90 | ΣR | Mean: | 74.73 | SD: | 27.10 | 95% CI: | 73.05 | 76.41 | ΣR | Mean: | 37.64 | SD: | 15.80 | 95% CI: | 36.66 | 38.62 |
| 0.99 | ΣR | Mean: | 75.38 | SD: | 27.58 | 95% CI: | 73.67 | 77.09 | ΣR | Mean: | 34.83 | SD: | 14.53 | 95% CI: | 33.93 | 35.73 |

Table A3 displays the statistical summaries of the simulation output for the number of diagnostic symptoms recognized, number of mission aborts, repair time as a result of 1,250 missions (5,000 flight hours) while varying the variance of the Weibull distribution determining M_A for the case with mean $P_C=0.99$. The beta distribution has parameters $\alpha_B=25$ and $\beta_B=.25$. The parameters of the Weibull distribution when $\alpha_W=0.5$ then $\beta_W=5$,

when $\alpha_W=1$ then $\beta_W=10$, and when $\alpha_W=1.5$ then $\beta_W=11.08$. This is data for Figures 8, 9, and 10.

Table A3

| α | LEGACY PROCESS | | | | | | CBM+ PROCESS | | | | | | | | | |
|----------|----------------|-------|--------------|-----|-------|---------|--------------|-------|---------------|-------|--------------|-----|-------|---------|-------|-------|
| 0.50 | $\sum DSs$ | Mean: | 4.08 | SD: | 1.98 | 95% CI: | 3.96 | 4.20 | $\sum DSs$ | Mean: | 7.26 | SD: | 2.64 | 95% CI: | 7.10 | 7.42 |
| 0.50 | $\sum Aborts$ | Mean: | 7.35 | SD: | 2.76 | 95% CI: | 7.18 | 7.52 | $\sum Aborts$ | Mean: | 4.17 | SD: | 2.07 | 95% CI: | 4.04 | 4.30 |
| 0.50 | $\sum R$ | Mean: | 70.13 | SD: | 26.62 | 95% CI: | 68.48 | 71.78 | $\sum R$ | Mean: | 42.64 | SD: | 18.51 | 95% CI: | 41.49 | 43.79 |
| 1.00 | $\sum DSs$ | Mean: | 6.08 | SD: | 2.48 | 95% CI: | 5.92 | 6.23 | $\sum DSs$ | Mean: | 10.40 | SD: | 3.28 | 95% CI: | 10.19 | 10.60 |
| 1.00 | $\sum Aborts$ | Mean: | 5.44 | SD: | 2.25 | 95% CI: | 5.30 | 5.58 | $\sum Aborts$ | Mean: | 1.12 | SD: | 1.03 | 95% CI: | 1.05 | 1.18 |
| 1.00 | $\sum R$ | Mean: | 75.86 | SD: | 27.82 | 95% CI: | 74.14 | 77.59 | $\sum R$ | Mean: | 36.54 | SD: | 16.35 | 95% CI: | 35.53 | 37.56 |
| 1.50 | $\sum DSs$ | Mean: | 6.79 | SD: | 2.66 | 95% CI: | 6.62 | 6.95 | $\sum DSs$ | Mean: | 11.03 | SD: | 3.36 | 95% CI: | 10.82 | 11.24 |
| 1.50 | $\sum Aborts$ | Mean: | 4.52 | SD: | 2.12 | 95% CI: | 4.39 | 4.65 | $\sum Aborts$ | Mean: | 0.28 | SD: | 0.51 | 95% CI: | 0.24 | 0.31 |
| 1.50 | $\sum R$ | Mean: | 74.81 | SD: | 27.39 | 95% CI: | 73.11 | 76.50 | $\sum R$ | Mean: | 34.78 | SD: | 14.80 | 95% CI: | 33.87 | 35.70 |

Tables A4 and A5 display the statistical summaries for the simulation output of the number of diagnostic symptoms recognized, number of mission aborts, repair time as a result of 1,250 missions (5,000 flight hours) while varying the variance of the Weibull distribution having mean 10 determining M_A for the cases where mean $P_C=0.50$ and mean $P_C=0.20$; the parameters of the beta distribution are $\alpha_B=25$ $\beta_B=25$ (when $P_C=0.50$) and $\alpha_B=25$ $\beta_B=100$ (when $P_C=0.20$). This is data for Figures 8, 9, and 10.

Table A4 ($P_C=0.50$)

| α | LEGACY PROCESS | | | | | | | | CBM+ PROCESS | | | | | | | |
|----------|----------------|-------|-------|-----|-------|---------|-------|-------|---------------|-------|-------|-----|-------|---------|-------|-------|
| 0.5 | $\sum DSs$ | Mean: | 4.19 | SD: | 2.02 | 95% CI: | 4.06 | 4.31 | $\sum DSs$ | Mean: | 6.39 | SD: | 2.54 | 95% CI: | 6.23 | 6.55 |
| 0.5 | $\sum Aborts$ | Mean: | 7.32 | SD: | 2.70 | 95% CI: | 7.15 | 7.49 | $\sum Aborts$ | Mean: | 5.12 | SD: | 2.28 | 95% CI: | 4.97 | 5.26 |
| 0.5 | $\sum R$ | Mean: | 70.71 | SD: | 26.44 | 95% CI: | 69.07 | 72.34 | $\sum R$ | Mean: | 53.00 | SD: | 21.19 | 95% CI: | 51.69 | 54.31 |
| 1 | $\sum DSs$ | Mean: | 5.99 | SD: | 2.44 | 95% CI: | 5.83 | 6.14 | $\sum DSs$ | Mean: | 9.30 | SD: | 3.12 | 95% CI: | 9.11 | 9.49 |
| 1 | $\sum Aborts$ | Mean: | 5.28 | SD: | 2.34 | 95% CI: | 5.13 | 5.42 | $\sum Aborts$ | Mean: | 1.96 | SD: | 1.45 | 95% CI: | 1.87 | 2.05 |
| 1 | $\sum R$ | Mean: | 74.59 | SD: | 28.77 | 95% CI: | 72.80 | 76.37 | $\sum R$ | Mean: | 51.20 | SD: | 20.26 | 95% CI: | 49.94 | 52.45 |
| 1.5 | $\sum DSs$ | Mean: | 6.72 | SD: | 2.50 | 95% CI: | 6.57 | 6.87 | $\sum DSs$ | Mean: | 10.35 | SD: | 3.10 | 95% CI: | 10.16 | 10.54 |
| 1.5 | $\sum Aborts$ | Mean: | 4.62 | SD: | 2.10 | 95% CI: | 4.49 | 4.75 | $\sum Aborts$ | Mean: | 1.00 | SD: | 0.98 | 95% CI: | 0.93 | 1.06 |
| 1.5 | $\sum R$ | Mean: | 75.54 | SD: | 26.39 | 95% CI: | 73.91 | 77.18 | $\sum R$ | Mean: | 50.22 | SD: | 18.71 | 95% CI: | 49.06 | 51.38 |

Table A5 ($P_C=0.20$)

| α | LEGACY PROCESS | | | | | | | | CBM+ PROCESS | | | | | | | |
|----------|----------------|-------|-------|-----|-------|---------|-------|-------|---------------|-------|-------|-----|-------|---------|-------|-------|
| 0.5 | $\sum DSs$ | Mean: | 4.06 | SD: | 1.98 | 95% CI: | 3.94 | 4.18 | $\sum DSs$ | Mean: | 4.88 | SD: | 2.27 | 95% CI: | 4.74 | 5.02 |
| 0.5 | $\sum Aborts$ | Mean: | 7.26 | SD: | 2.62 | 95% CI: | 7.09 | 7.42 | $\sum Aborts$ | Mean: | 6.44 | SD: | 2.45 | 95% CI: | 6.29 | 6.59 |
| 0.5 | $\sum R$ | Mean: | 70.19 | SD: | 26.71 | 95% CI: | 68.54 | 71.85 | $\sum R$ | Mean: | 63.61 | SD: | 24.94 | 95% CI: | 62.06 | 65.15 |
| 1 | $\sum DSs$ | Mean: | 6.10 | SD: | 2.47 | 95% CI: | 5.95 | 6.25 | $\sum DSs$ | Mean: | 7.56 | SD: | 2.72 | 95% CI: | 7.39 | 7.72 |
| 1 | $\sum Aborts$ | Mean: | 5.40 | SD: | 2.39 | 95% CI: | 5.25 | 5.54 | $\sum Aborts$ | Mean: | 3.94 | SD: | 2.09 | 95% CI: | 3.81 | 4.07 |
| 1 | $\sum R$ | Mean: | 75.93 | SD: | 28.37 | 95% CI: | 74.17 | 77.68 | $\sum R$ | Mean: | 68.00 | SD: | 25.51 | 95% CI: | 66.42 | 69.58 |
| 1.5 | $\sum DSs$ | Mean: | 7.04 | SD: | 2.59 | 95% CI: | 6.88 | 7.20 | $\sum DSs$ | Mean: | 8.67 | SD: | 2.95 | 95% CI: | 8.49 | 8.85 |
| 1.5 | $\sum Aborts$ | Mean: | 4.54 | SD: | 2.19 | 95% CI: | 4.41 | 4.68 | $\sum Aborts$ | Mean: | 2.91 | SD: | 1.72 | 95% CI: | 2.80 | 3.01 |
| 1.5 | $\sum R$ | Mean: | 75.81 | SD: | 27.79 | 95% CI: | 74.08 | 77.53 | $\sum R$ | Mean: | 68.02 | SD: | 25.21 | 95% CI: | 66.45 | 69.58 |

Table A6 displays the statistical summaries of simulation output for the number of false positives and the repair (inspection) times as a result of 1,250 missions (5,000 flight hours) while varying the false positive arrival rate; the parameters of the beta distribution are $\alpha_B=25$ and $\beta_B=.25$; the parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$. This is an expanded version of Table 12.

Table A6

| False Positive Rate | CBM+ PROCESS (NUMBER OF FALSE POSITIVE ARRIVALS) | | | | | | | |
|---------------------|--|-------|----------------|-----|--------|---------|---------|---------|
| 0.9999 | Σ FP | Mean: | 1238.57 | SD: | 3.31 | 95% CI: | 1238.36 | 1238.78 |
| 0.90 | Σ FP | Mean: | 1115.29 | SD: | 11.18 | 95% CI: | 1114.59 | 1115.98 |
| 0.80 | Σ FP | Mean: | 990.51 | SD: | 14.47 | 95% CI: | 989.61 | 991.41 |
| 0.70 | Σ FP | Mean: | 866.70 | SD: | 16.58 | 95% CI: | 865.67 | 867.73 |
| 0.60 | Σ FP | Mean: | 743.41 | SD: | 17.13 | 95% CI: | 742.34 | 744.47 |
| 0.50 | Σ FP | Mean: | 620.23 | SD: | 17.69 | 95% CI: | 619.14 | 621.33 |
| 0.40 | Σ FP | Mean: | 495.29 | SD: | 16.85 | 95% CI: | 494.25 | 496.34 |
| 0.30 | Σ FP | Mean: | 372.07 | SD: | 16.24 | 95% CI: | 371.06 | 373.08 |
| 0.20 | Σ FP | Mean: | 247.05 | SD: | 14.09 | 95% CI: | 246.18 | 247.92 |
| 0.10 | Σ FP | Mean: | 124.34 | SD: | 10.44 | 95% CI: | 123.69 | 124.98 |
| 0.0001 | Σ FP | Mean: | 0.14 | SD: | 0.36 | 95% CI: | 0.11 | 0.16 |
| False Positive Rate | CBM+ PROCESS (REPAIR TIME INCURRED DUE TO FALSE POSITIVE ARRIVALS) | | | | | | | |
| 0.9999 | Σ FP Time | Mean: | 3717.41 | SD: | 105.16 | 95% CI: | 3710.89 | 3723.93 |
| 0.90 | Σ FP Time | Mean: | 3343.55 | SD: | 106.54 | 95% CI: | 3336.95 | 3350.15 |
| 0.80 | Σ FP Time | Mean: | 2969.66 | SD: | 104.41 | 95% CI: | 2963.19 | 2976.13 |
| 0.70 | Σ FP Time | Mean: | 2598.47 | SD: | 104.49 | 95% CI: | 2591.99 | 2604.94 |
| 0.60 | Σ FP Time | Mean: | 2228.17 | SD: | 98.01 | 95% CI: | 2222.10 | 2234.25 |
| 0.50 | Σ FP Time | Mean: | 1861.03 | SD: | 89.15 | 95% CI: | 1855.50 | 1866.55 |
| 0.40 | Σ FP Time | Mean: | 1490.28 | SD: | 85.40 | 95% CI: | 1484.98 | 1495.57 |
| 0.30 | Σ FP Time | Mean: | 1118.76 | SD: | 74.55 | 95% CI: | 1114.14 | 1123.38 |
| 0.20 | Σ FP Time | Mean: | 741.94 | SD: | 62.68 | 95% CI: | 738.05 | 745.82 |
| 0.10 | Σ FP Time | Mean: | 371.62 | SD: | 47.00 | 95% CI: | 368.71 | 374.54 |
| 0.0001 | Σ FP Time | Mean: | 0.42 | SD: | 1.64 | 95% CI: | 0.32 | 0.52 |

Table A7 displays the statistical summaries of the output of simulations for the total repair time (total repair time = diagnostic symptom repair time + false positive repair time) as a result of 1,250 missions (5,000 flight hours) while varying the false positive arrival rate. The parameters of the beta distribution are $\alpha_B=25$ and $\beta_B=.25$; the parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$. This is an expanded version of Table 14.

Table A7

| False Positive Rate | CBM+ PROCESS (TOTAL REPAIR TIME=DS REPAIR TIME+FALSE POSITIVE REPAIR TIME) | | | | | | |
|---------------------|--|-------|---------------|-----|-------|---------|---------------|
| 0.10 | $\Sigma R + \Sigma FP$ Time | Mean: | 406.13 | SD: | 48.87 | 95% CI: | 403.11 409.16 |
| 0.09 | $\Sigma R + \Sigma FP$ Time | Mean: | 369.59 | SD: | 46.37 | 95% CI: | 366.71 372.46 |
| 0.08 | $\Sigma R + \Sigma FP$ Time | Mean: | 330.84 | SD: | 42.89 | 95% CI: | 328.18 333.50 |
| 0.07 | $\Sigma R + \Sigma FP$ Time | Mean: | 291.50 | SD: | 42.19 | 95% CI: | 288.89 294.12 |
| 0.06 | $\Sigma R + \Sigma FP$ Time | Mean: | 257.54 | SD: | 38.12 | 95% CI: | 255.18 259.91 |
| 0.05 | $\Sigma R + \Sigma FP$ Time | Mean: | 221.93 | SD: | 37.29 | 95% CI: | 219.61 224.24 |
| 0.04 | $\Sigma R + \Sigma FP$ Time | Mean: | 185.08 | SD: | 32.49 | 95% CI: | 183.06 187.09 |
| 0.03 | $\Sigma R + \Sigma FP$ Time | Mean: | 146.10 | SD: | 30.02 | 95% CI: | 144.24 147.96 |
| 0.02 | $\Sigma R + \Sigma FP$ Time | Mean: | 108.97 | SD: | 25.81 | 95% CI: | 107.38 110.57 |
| 0.01 | $\Sigma R + \Sigma FP$ Time | Mean: | 71.91 | SD: | 20.47 | 95% CI: | 70.64 73.17 |
| 0.0001 | $\Sigma R + \Sigma FP$ Time | Mean: | 36.06 | SD: | 15.43 | 95% CI: | 35.10 37.02 |

Table A8 displays the statistical summaries of simulation output for the time awaiting replacement components as a result of 1,250 missions (5,000 flight hours) while varying P_{OH} when mean P_C is 0.99 and the mean time until the replacement component arrives is 3 days. The parameters of the beta distribution are $\alpha_B=25$ and $\beta_B=.25$; the parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$. The time until a component replacement arrives has an exponential distribution. This is data for Figure 12.

Table A8

| $P_{OH HAND}$ | LEGACY PROCESS | | | | | | CBM+ PROCESS | | | | | |
|---------------|----------------|-------|--------------|-----|-------|---------|--------------|-------------|-------|-------------|-----|------------------------|
| 0.9999 | ΣAS | Mean: | 0.00 | SD: | 0.09 | 95% CI: | 0.00 0.01 | ΣAS | Mean: | 0.00 | SD: | 0.00 95% CI: 0.00 0.00 |
| 0.90 | ΣAS | Mean: | 1.72 | SD: | 3.23 | 95% CI: | 1.52 1.92 | ΣAS | Mean: | 0.45 | SD: | 1.64 95% CI: 0.35 0.55 |
| 0.80 | ΣAS | Mean: | 3.57 | SD: | 4.77 | 95% CI: | 3.28 3.87 | ΣAS | Mean: | 0.87 | SD: | 2.27 95% CI: 0.73 1.01 |
| 0.70 | ΣAS | Mean: | 5.03 | SD: | 5.59 | 95% CI: | 4.68 5.38 | ΣAS | Mean: | 1.26 | SD: | 2.83 95% CI: 1.08 1.44 |
| 0.60 | ΣAS | Mean: | 7.05 | SD: | 6.76 | 95% CI: | 6.63 7.47 | ΣAS | Mean: | 1.83 | SD: | 3.27 95% CI: 1.63 2.03 |
| 0.50 | ΣAS | Mean: | 7.99 | SD: | 7.05 | 95% CI: | 7.56 8.43 | ΣAS | Mean: | 2.09 | SD: | 3.40 95% CI: 1.88 2.30 |
| 0.40 | ΣAS | Mean: | 10.46 | SD: | 8.02 | 95% CI: | 9.96 10.95 | ΣAS | Mean: | 3.01 | SD: | 4.19 95% CI: 2.75 3.27 |
| 0.30 | ΣAS | Mean: | 11.75 | SD: | 8.58 | 95% CI: | 11.22 12.28 | ΣAS | Mean: | 3.15 | SD: | 4.37 95% CI: 2.88 3.42 |
| 0.20 | ΣAS | Mean: | 13.37 | SD: | 9.05 | 95% CI: | 12.81 13.93 | ΣAS | Mean: | 3.36 | SD: | 4.12 95% CI: 3.10 3.61 |
| 0.10 | ΣAS | Mean: | 15.50 | SD: | 9.47 | 95% CI: | 14.91 16.08 | ΣAS | Mean: | 4.23 | SD: | 5.65 95% CI: 3.88 4.58 |
| 0.0001 | ΣAS | Mean: | 16.77 | SD: | 10.16 | 95% CI: | 16.14 17.40 | ΣAS | Mean: | 4.72 | SD: | 5.57 95% CI: 4.37 5.06 |

Table A9 displays the statistical summaries of simulation output for the time awaiting replacement components as a result of 1,250 missions (5,000 flight hours) while varying P_{OH} when mean P_C is 0.50 and the mean time until the replacement component arrives is 3 days. The parameters of the beta distribution are $\alpha_B=25$ and $\beta_B=25$; the parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$. The time until a replacement component arrives has an exponential distribution. This is data for Figure 13.

Table A9

| P _{ON HAND} | LEGACY PROCESS | | | | | | | | CBM+ PROCESS | | | | | | | |
|----------------------|----------------|-------|-------|-----|-------|---------|-------|-------|--------------|-------|------|-----|------|---------|------|------|
| 0.9999 | ΣAS | Mean: | 0.00 | SD: | 0.01 | 95% CI: | 0.00 | 0.00 | ΣAS | Mean: | 0.00 | SD: | 0.00 | 95% CI: | 0.00 | 0.00 |
| 0.90 | ΣAS | Mean: | 1.76 | SD: | 3.47 | 95% CI: | 1.55 | 1.98 | ΣAS | Mean: | 0.69 | SD: | 1.86 | 95% CI: | 0.58 | 0.81 |
| 0.80 | ΣAS | Mean: | 3.41 | SD: | 4.53 | 95% CI: | 3.13 | 3.69 | ΣAS | Mean: | 1.38 | SD: | 2.80 | 95% CI: | 1.21 | 1.56 |
| 0.70 | ΣAS | Mean: | 4.98 | SD: | 5.55 | 95% CI: | 4.64 | 5.33 | ΣAS | Mean: | 2.26 | SD: | 3.80 | 95% CI: | 2.02 | 2.49 |
| 0.60 | ΣAS | Mean: | 6.88 | SD: | 6.32 | 95% CI: | 6.48 | 7.27 | ΣAS | Mean: | 2.70 | SD: | 3.86 | 95% CI: | 2.46 | 2.94 |
| 0.50 | ΣAS | Mean: | 8.69 | SD: | 6.70 | 95% CI: | 8.27 | 9.10 | ΣAS | Mean: | 3.43 | SD: | 4.55 | 95% CI: | 3.15 | 3.71 |
| 0.40 | ΣAS | Mean: | 10.38 | SD: | 8.02 | 95% CI: | 9.89 | 10.88 | ΣAS | Mean: | 3.92 | SD: | 4.66 | 95% CI: | 3.64 | 4.21 |
| 0.30 | ΣAS | Mean: | 11.73 | SD: | 8.35 | 95% CI: | 11.21 | 12.25 | ΣAS | Mean: | 5.11 | SD: | 5.68 | 95% CI: | 4.76 | 5.46 |
| 0.20 | ΣAS | Mean: | 13.44 | SD: | 9.00 | 95% CI: | 12.88 | 14.00 | ΣAS | Mean: | 5.50 | SD: | 5.67 | 95% CI: | 5.15 | 5.85 |
| 0.10 | ΣAS | Mean: | 15.31 | SD: | 9.27 | 95% CI: | 14.73 | 15.88 | ΣAS | Mean: | 6.30 | SD: | 6.12 | 95% CI: | 5.92 | 6.68 |
| 0.0001 | ΣAS | Mean: | 17.16 | SD: | 10.06 | 95% CI: | 16.53 | 17.78 | ΣAS | Mean: | 6.77 | SD: | 6.14 | 95% CI: | 6.39 | 7.15 |

Table A10 displays statistical summaries of simulation output for the time awaiting replacement components as a result of 1,250 missions (5,000 flight hours) while varying P_{OH} when mean P_C is 0.20 and the mean time until the replacement component arrives is 3 days. The parameters of the beta distribution are $\alpha_B=25$ and $\beta_B=100$; the parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$. The time until a replacement component arrives has an exponential distribution. This is data for Figure 14.

Table A10

| P _{ON HAND} | LEGACY PROCESS | | | | | | | | CBM+ PROCESS | | | | | | | |
|----------------------|----------------|-------|-------|-----|-------|---------|-------|-------|--------------|-------|-------|-----|------|---------|-------|-------|
| 0.9999 | ΣAS | Mean: | 0.00 | SD: | 0.00 | 95% CI: | 0.00 | 0.00 | ΣAS | Mean: | 0.00 | SD: | 0.00 | 95% CI: | 0.00 | 0.00 |
| 0.90 | ΣAS | Mean: | 1.69 | SD: | 3.10 | 95% CI: | 1.50 | 1.88 | ΣAS | Mean: | 1.32 | SD: | 2.91 | 95% CI: | 1.14 | 1.50 |
| 0.80 | ΣAS | Mean: | 3.34 | SD: | 4.51 | 95% CI: | 3.07 | 3.62 | ΣAS | Mean: | 2.67 | SD: | 4.05 | 95% CI: | 2.42 | 2.92 |
| 0.70 | ΣAS | Mean: | 5.06 | SD: | 5.17 | 95% CI: | 4.74 | 5.38 | ΣAS | Mean: | 3.81 | SD: | 4.92 | 95% CI: | 3.51 | 4.12 |
| 0.60 | ΣAS | Mean: | 6.37 | SD: | 6.04 | 95% CI: | 6.00 | 6.75 | ΣAS | Mean: | 5.25 | SD: | 5.43 | 95% CI: | 4.91 | 5.58 |
| 0.50 | ΣAS | Mean: | 8.78 | SD: | 7.08 | 95% CI: | 8.34 | 9.22 | ΣAS | Mean: | 5.92 | SD: | 5.74 | 95% CI: | 5.57 | 6.28 |
| 0.40 | ΣAS | Mean: | 10.14 | SD: | 8.04 | 95% CI: | 9.64 | 10.64 | ΣAS | Mean: | 8.03 | SD: | 7.25 | 95% CI: | 7.58 | 8.48 |
| 0.30 | ΣAS | Mean: | 12.23 | SD: | 8.40 | 95% CI: | 11.71 | 12.75 | ΣAS | Mean: | 9.31 | SD: | 7.65 | 95% CI: | 8.84 | 9.79 |
| 0.20 | ΣAS | Mean: | 13.77 | SD: | 9.34 | 95% CI: | 13.19 | 14.34 | ΣAS | Mean: | 10.08 | SD: | 7.37 | 95% CI: | 9.62 | 10.53 |
| 0.10 | ΣAS | Mean: | 15.16 | SD: | 9.55 | 95% CI: | 14.57 | 15.75 | ΣAS | Mean: | 11.21 | SD: | 8.33 | 95% CI: | 10.69 | 11.73 |
| 0.0001 | ΣAS | Mean: | 17.16 | SD: | 10.53 | 95% CI: | 16.51 | 17.81 | ΣAS | Mean: | 12.42 | SD: | 8.69 | 95% CI: | 11.88 | 12.96 |

Table A11 displays the statistical summaries of simulation output for the time awaiting replacement components as a result of 1,250 missions (5,000 flight hours) while varying P_{OH} when P_C is 0.99 and the mean time until the replacement component arrives is 10 days. The parameters of the beta distribution are $\alpha_B=25$ and $\beta_B=.25$; the parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$. The time until a replacement component arrives has an exponential distribution. This is data for Figure 15.

Table A11

| P _{ON HAND} | LEGACY PROCESS | | | | | | | | CBM+ PROCESS | | | | | | | |
|----------------------|----------------|-------|-------|-----|-------|---------|-------|-------|--------------|-------|-------|-----|-------|---------|-------|-------|
| 0.9999 | ΣAS | Mean: | 0.00 | SD: | 0.12 | 95% CI: | 0.00 | 0.01 | ΣAS | Mean: | 0.00 | SD: | 0.00 | 95% CI: | 0.00 | 0.00 |
| 0.90 | ΣAS | Mean: | 9.44 | SD: | 13.44 | 95% CI: | 8.60 | 10.27 | ΣAS | Mean: | 6.67 | SD: | 11.20 | 95% CI: | 5.98 | 7.36 |
| 0.80 | ΣAS | Mean: | 17.45 | SD: | 19.30 | 95% CI: | 16.25 | 18.64 | ΣAS | Mean: | 12.49 | SD: | 14.44 | 95% CI: | 11.59 | 13.38 |
| 0.70 | ΣAS | Mean: | 27.42 | SD: | 23.59 | 95% CI: | 25.95 | 28.88 | ΣAS | Mean: | 19.50 | SD: | 18.93 | 95% CI: | 18.33 | 20.67 |
| 0.60 | ΣAS | Mean: | 36.92 | SD: | 27.18 | 95% CI: | 35.23 | 38.60 | ΣAS | Mean: | 25.90 | SD: | 23.77 | 95% CI: | 24.43 | 27.37 |
| 0.50 | ΣAS | Mean: | 42.93 | SD: | 29.17 | 95% CI: | 41.12 | 44.74 | ΣAS | Mean: | 33.20 | SD: | 25.91 | 95% CI: | 31.60 | 34.81 |
| 0.40 | ΣAS | Mean: | 53.36 | SD: | 33.14 | 95% CI: | 51.30 | 55.41 | ΣAS | Mean: | 40.31 | SD: | 29.13 | 95% CI: | 38.51 | 42.12 |
| 0.30 | ΣAS | Mean: | 64.97 | SD: | 36.21 | 95% CI: | 62.72 | 67.21 | ΣAS | Mean: | 46.02 | SD: | 31.59 | 95% CI: | 44.06 | 47.98 |
| 0.20 | ΣAS | Mean: | 73.09 | SD: | 38.88 | 95% CI: | 70.68 | 75.50 | ΣAS | Mean: | 52.48 | SD: | 31.03 | 95% CI: | 50.55 | 54.40 |
| 0.10 | ΣAS | Mean: | 80.22 | SD: | 40.80 | 95% CI: | 77.69 | 82.75 | ΣAS | Mean: | 60.02 | SD: | 34.32 | 95% CI: | 57.90 | 62.15 |
| 0.0001 | ΣAS | Mean: | 88.67 | SD: | 41.58 | 95% CI: | 86.09 | 91.25 | ΣAS | Mean: | 63.91 | SD: | 34.87 | 95% CI: | 61.75 | 66.07 |

Table A12 displays the statistical summaries of simulation output for the time awaiting replacement components as a result of 1,250 missions (5,000 flight hours) while varying P_{OH} when P_C is 0.50 and the mean time until the replacement component arrives is 10 days. The parameters of the beta distribution are $\alpha_B=25$ and $\beta_B=25$; the parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$. The time until a replacement component arrives has an exponential distribution. This is data for Figure 16.

Table A12

| $P_{ON HAND}$ | LEGACY PROCESS | | | | | | | | CBM+ PROCESS | | | | | | | |
|---------------|----------------|-------|--------------|-----|-------|---------|-------|-------|--------------|-------|--------------|-----|-------|---------|-------|-------|
| 0.9999 | ΣAS | Mean: | 0.01 | SD: | 0.13 | 95% CI: | 0.00 | 0.01 | ΣAS | Mean: | 0.00 | SD: | 0.00 | 95% CI: | 0.00 | 0.00 |
| 0.90 | ΣAS | Mean: | 9.48 | SD: | 13.96 | 95% CI: | 8.61 | 10.34 | ΣAS | Mean: | 7.47 | SD: | 12.05 | 95% CI: | 6.73 | 8.22 |
| 0.80 | ΣAS | Mean: | 17.40 | SD: | 17.80 | 95% CI: | 16.30 | 18.50 | ΣAS | Mean: | 14.60 | SD: | 17.07 | 95% CI: | 13.54 | 15.66 |
| 0.70 | ΣAS | Mean: | 27.14 | SD: | 24.12 | 95% CI: | 25.65 | 28.63 | ΣAS | Mean: | 21.73 | SD: | 21.52 | 95% CI: | 20.39 | 23.06 |
| 0.60 | ΣAS | Mean: | 36.32 | SD: | 26.46 | 95% CI: | 34.68 | 37.96 | ΣAS | Mean: | 27.52 | SD: | 23.12 | 95% CI: | 26.08 | 28.95 |
| 0.50 | ΣAS | Mean: | 46.22 | SD: | 30.29 | 95% CI: | 44.34 | 48.10 | ΣAS | Mean: | 35.94 | SD: | 25.66 | 95% CI: | 34.35 | 37.53 |
| 0.40 | ΣAS | Mean: | 54.79 | SD: | 33.17 | 95% CI: | 52.73 | 56.85 | ΣAS | Mean: | 43.21 | SD: | 30.15 | 95% CI: | 41.35 | 45.08 |
| 0.30 | ΣAS | Mean: | 63.01 | SD: | 35.55 | 95% CI: | 60.80 | 65.21 | ΣAS | Mean: | 51.58 | SD: | 31.18 | 95% CI: | 49.65 | 53.51 |
| 0.20 | ΣAS | Mean: | 72.70 | SD: | 38.17 | 95% CI: | 70.34 | 75.07 | ΣAS | Mean: | 57.41 | SD: | 33.00 | 95% CI: | 55.37 | 59.46 |
| 0.10 | ΣAS | Mean: | 81.96 | SD: | 39.36 | 95% CI: | 79.52 | 84.40 | ΣAS | Mean: | 65.56 | SD: | 36.87 | 95% CI: | 63.28 | 67.85 |
| 0.0001 | ΣAS | Mean: | 89.19 | SD: | 42.49 | 95% CI: | 86.56 | 91.83 | ΣAS | Mean: | 71.63 | SD: | 38.87 | 95% CI: | 69.22 | 74.04 |

Table A13 displays the statistical summaries of simulation output for the time awaiting replacement components as a result of 1,250 missions (5,000 flight hours) while varying P_{OH} when P_C is 0.20 and the mean time until the replacement component arrives is 10 days. The parameters of the beta distribution are $\alpha_B=25$ and $\beta_B=100$; the parameters of the Weibull distribution are $\alpha_W=1.5$ and $\beta_W=11.08$. The time until a replacement component arrives has an exponential distribution. This is data for Figure 17.

Table A13

| $P_{ON HAND}$ | LEGACY PROCESS | | | | | | | | CBM+ PROCESS | | | | | | | |
|---------------|----------------|-------|--------------|-----|-------|---------|-------|-------|--------------|-------|--------------|-----|-------|---------|-------|-------|
| 0.9999 | ΣAS | Mean: | 0.00 | SD: | 0.04 | 95% CI: | 0.00 | 0.00 | ΣAS | Mean: | 0.00 | SD: | 0.00 | 95% CI: | 0.00 | 0.00 |
| 0.90 | ΣAS | Mean: | 9.34 | SD: | 13.18 | 95% CI: | 8.53 | 10.16 | ΣAS | Mean: | 8.54 | SD: | 12.64 | 95% CI: | 7.76 | 9.33 |
| 0.80 | ΣAS | Mean: | 18.52 | SD: | 20.35 | 95% CI: | 17.25 | 19.78 | ΣAS | Mean: | 15.59 | SD: | 17.45 | 95% CI: | 14.51 | 16.67 |
| 0.70 | ΣAS | Mean: | 27.17 | SD: | 23.59 | 95% CI: | 25.70 | 28.63 | ΣAS | Mean: | 24.82 | SD: | 22.59 | 95% CI: | 23.42 | 26.22 |
| 0.60 | ΣAS | Mean: | 35.22 | SD: | 26.04 | 95% CI: | 33.60 | 36.83 | ΣAS | Mean: | 33.89 | SD: | 26.58 | 95% CI: | 32.24 | 35.54 |
| 0.50 | ΣAS | Mean: | 44.64 | SD: | 29.66 | 95% CI: | 42.80 | 46.47 | ΣAS | Mean: | 41.84 | SD: | 29.17 | 95% CI: | 40.03 | 43.64 |
| 0.40 | ΣAS | Mean: | 55.17 | SD: | 33.73 | 95% CI: | 53.08 | 57.26 | ΣAS | Mean: | 50.15 | SD: | 31.35 | 95% CI: | 48.21 | 52.10 |
| 0.30 | ΣAS | Mean: | 64.12 | SD: | 35.57 | 95% CI: | 61.92 | 66.33 | ΣAS | Mean: | 59.46 | SD: | 34.52 | 95% CI: | 57.32 | 61.60 |
| 0.20 | ΣAS | Mean: | 72.38 | SD: | 37.69 | 95% CI: | 70.04 | 74.71 | ΣAS | Mean: | 67.09 | SD: | 37.19 | 95% CI: | 64.78 | 69.39 |
| 0.10 | ΣAS | Mean: | 81.59 | SD: | 40.41 | 95% CI: | 79.09 | 84.10 | ΣAS | Mean: | 73.96 | SD: | 36.69 | 95% CI: | 71.68 | 76.23 |
| 0.0001 | ΣAS | Mean: | 89.03 | SD: | 41.85 | 95% CI: | 86.44 | 91.62 | ΣAS | Mean: | 81.51 | SD: | 40.35 | 95% CI: | 79.01 | 84.01 |

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